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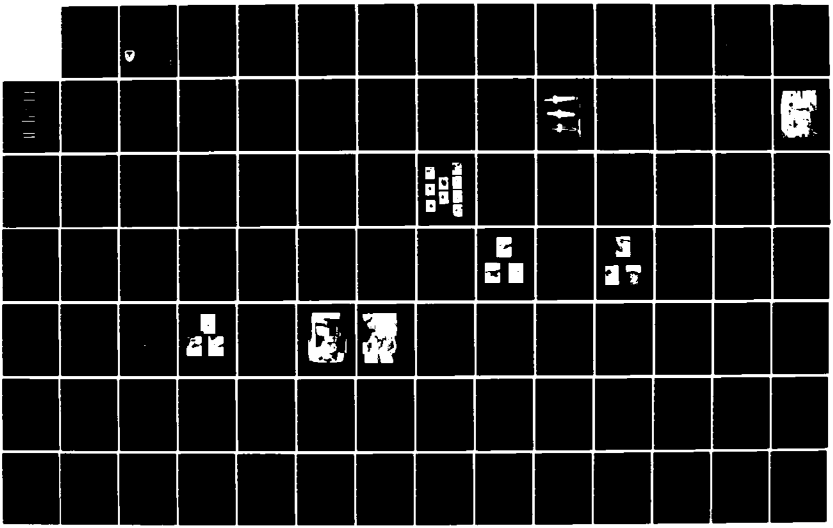

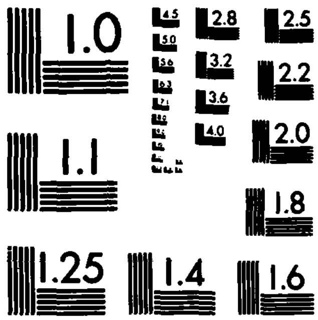

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T700 CUTTER LIFE IMPROVEMENT PROGRAM

Reduction in Number of Cutters Used for Milling Blisk and Impeller Airfoils

David M. Dombrowski
General Electric Company
Aircraft Engine Business Group
1000 Western Avenue
Lynn, Massachusetts 01910

September 1984

FINAL REPORT

Contract No. DAAK50-81-C-0029

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United States Army
AVIATION RESEARCH AND DEVELOPMENT COMMAND

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of the T700 Cutter Life Improvement Program was to reduce the number of cutters used for the blisk and impeller airfoil milling operations from 134 to less than 90 cutters per engine set, thereby reducing T700 engine cost. The objective was achieved by stiffening toolholders, improving cutter designs, and changing cutter material. Other parameters investigated include cutting speeds, cutting fluids, surface coating, and surface treatment of the cutters.

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Phase I of the program was mainly analytical, phase II involved more extensive laboratory testing of cutter designs, materials, cutting fluids, machining parameters, and production verification of the laboratory results.

A computer simulation program developed by Professor Nathan H. Cook, Professor of Mechanical Engineering at Massachusetts Institute of Technology was used to study effect of spindle and tool compliance and eccentricity, cutter geometry, and cutting parameters on cutting forces and tool deflections. This is the first computer simulation program to accurately predict milling forces and tool breakage when tool deflection is significant. It may also be used as an aid to optimize other milling systems.

Cutter failure investigation was conducted to understand modes/causes of tool failure. As a result, adjustments to NC program were made, deficiencies in the cutter geometry were corrected to improve cutter life.

Originator - supplied keywords include:

A detailed study of toolholders including flexibility, gripping capabilities, stiffness, and deflection characteristics, resulted in the selection of double angle collet toolholders for use in production. This improvement reduced the usage of all cutter types.

A statistical laboratory evaluation of cutter materials, geometries, cutting speeds, and feeds was designed and completed. This was followed by further testing in actual production environment. This effort resulted in a new cutter material.

The cutter inspection functional specification was prepared in which inspection requirements were outlined for all of the cutters. Based on review of the functional specification by the potential sources for the inspection equipment, a final specification was prepared.

Four tabulated drawings were produced using interactive graphics to accurately define the 10 cutters used in T700 blisk and impeller milling operations.

At the start of this program, a total of 134 cutters were used to produce the T700 compressor section rotating components for each engine. Current cutter usage is 88 cutters per engine. This reduction represents a savings of 28% of the cutters on Stage 1, 46% on Stage 2, 7% on Stages 3 and 4, 22% on Stage 5, and a 41% reduction for the impeller. These reductions represent a projected savings to the U.S. Government of $7.8 million over the next 10 years.

ACKNOWLEDGEMENTS

A number of organizations and people made important contributions to this program.

The T700 Cutter Life Improvement Program was made possible by the US Army Troop Support and Aviation Material Readiness Command in St. Louis, Missouri. The support of Nirmal Singh, and Bill Hunt are greatly appreciated.

Cutting force data and contour milling force simulation data was obtained under the direction of Professor Nathan H. Cook of the Massachusetts Institute of Technology, Cambridge, Massachusetts.

The contributions and efforts of the General Electric Lynn Tool Grinding department under the direction of Ted Hoosick; the General Electric Hooksett Manufacturing facilities under Norman Russell and Don Connor; the Carboloy Division of General Electric for cutter material analysis; and Charles Anton of General Electric Lynn Data Analysis were all vital to the this program. Conrad Gerhartz worked diligently to develop the functional specification for cutter inspection equipment. Alex Koso of A.K. Associates, developed the final specification for cutter inspection equipment.

Technical help from Wayne Growitz and Alan Barile are greatly appreciated. The supervision provided by William Sullivan, William Lightfoot, Gerry Sirois, and John Hsia was invaluable. Ken Anastasi's dedication to the program as principle technician responsible for production verification of laboratory results was flawless.

The principle investigator of the initial portion of the project was Paul Hartung before being taken over by the author. Paul's initial efforts can be credited for the positive direction of this program.

And to all those, too numerous to mention by name, who, through their effort, suggestions and patience, have made this program a success, thank you.

PREFACE

The reader will find this report details the two phases of the T700 Cutter Life Improvement Program namely:

Phase I: Investigation of Cutter Parameters that affect tool life. This report describes the initial efforts, including: a literature search for improved toolholders, cutting fluids, cutter materials, coated cutters, and cryogenically treated cutters; a cutter usage survey; and investigation of cutter failure.

Phase II: Optimization and Verification describes the simulation of the milling process; and cutting fluid evaluation; statistically designed Laboratory Controlled Cutter evaluation of cutting parameters; and verification of the laboratory results in the manufacturing environment. A specification for a cutter inspection station, and detailed cutter drawings were also completed.

The savings directly attributed to this program are detailed in the Program Savings section.

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SUMMARY OF THE CUTTER LIFE IMPROVEMENT PROGRAM

SUMMARY OF T700 CUTTER LIFE IMPROVEMENT PROGRAM

INTRODUCTION

The General Electric T700 engine is a 1500-2200 shaft horsepower turboshaft engine developed to power the U.S. Army's new generation of utility and attack helicopters. The advanced technology T700 provides major improvements in reliability, maintainability, and fuel efficiency. These features substantially reduced life cycle cost and set new standards for engines in its class. Some T700 applications are the Sikorsky UH-60A Black Hawk and the Hughes AH-64 Advanced Attack Helicopter for the Army and the Sikorsky SH-60B Seahawk for the Navy.

The T700 Cutter Life Improvement Program is one of many programs designed to reduce the cost of the T700 engine. This program concentrated on improving the life of 10 milling cutters used to machine aerodynamic surfaces (airfoils) on the five axial stages and one centrifugal stage (impeller) in the manufacture of T700 compressor section components shown in Figure 1. The results of this two-year effort are described in this report.

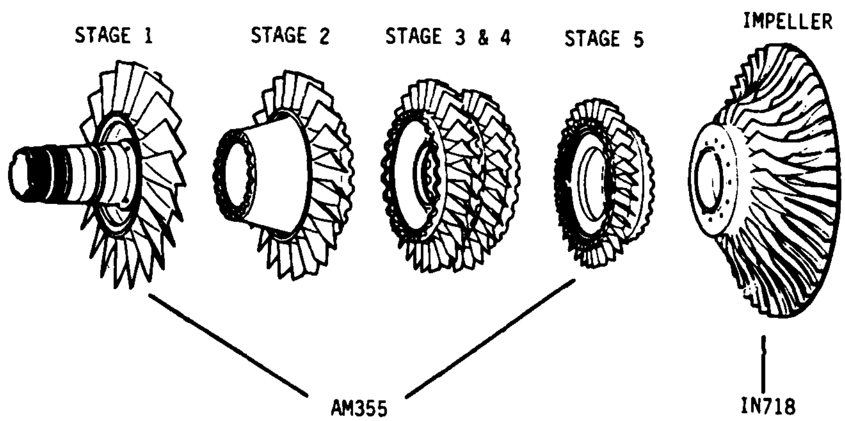

Figure 1. T700 Compressor Section Rotating Parts.

BACKGROUND

The T700 engine compressor airfoils are machined on the 4-spindle 5-axis CNC milling machine. This process was developed under Army MMT Program Contract No. DAAJ01-75-C-0844 and implemented under Army Contracts DAAJ01-77-C-0034 and DAAK50-82-E-0001. This represented a substantial cost reduction from the initial single spindle pantograph duplicating milling and time-consuming manual finishing techniques.

In 1981, at the beginning of the T700 Cutter Life Improvement Program, an average of 134 cutters were being used to machine the components for each T700 compressor section. A 33% reduction in cutter usage (134 to 90) was predicted as well as a significant reduction in cutter change time. These reductions, when applied to the projected (year 1980) 4,000 military T700 engines, accounted for a significant overall savings. The importance of this program has increased since the projected Army T700 engines production schedules will require over 4,000 engines in the next 10 years.

The manufacture of the geometrically complex T700 blisks and impellers, made from difficult-to-machine superalloys such as IN718 and AM355, necessitates the use of unique state-of-the-art equipment such as 8-axis CNC cutter grinding equipment, high resolution cutter inspection equipment, complex milling cutters and four-spindle five-axis computer numerically controlled (CNC) milling machines. The use of milling cutters with long extensions and thin diameters often result in breakage and short cutter life.

Three roughing cutters, four finishing cutters, and three platform cutters (see Figure 2, pg 3), all with complex geometries are used to produce the T700 compressor rotor assembly. This assembly consists of five stages of axial compressor blisks (see Appendix G) and a single stage centrifugal compressor (impeller). The cutters, ground from solid carbide (Carboloy 883) rod, have 4 to 15 flutes, range from 5/16 to 3/16 inches in diameter, and 3-1/2 to 4 inches in length. Figures 3A and 3B (pgs 4-5) show the geometry of 10 typical cutters. In September 1981, a two-phase program to improve the life of these cutters was begun.

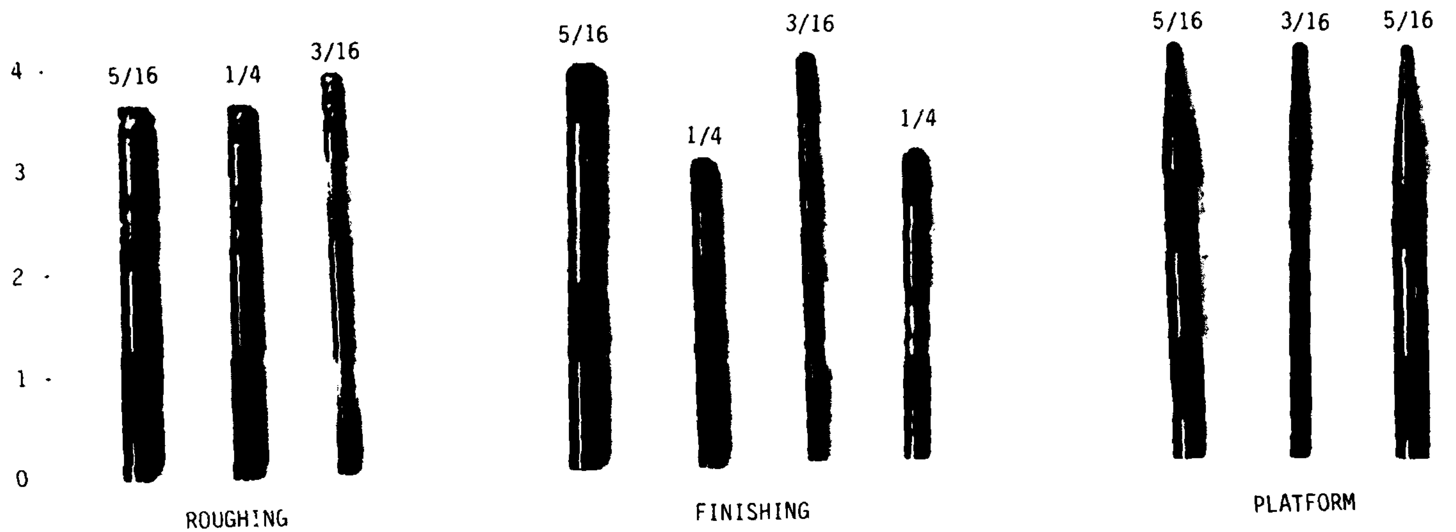

Figure 2. Cutters Required for Production of the T700 Compressor Rotor Components.

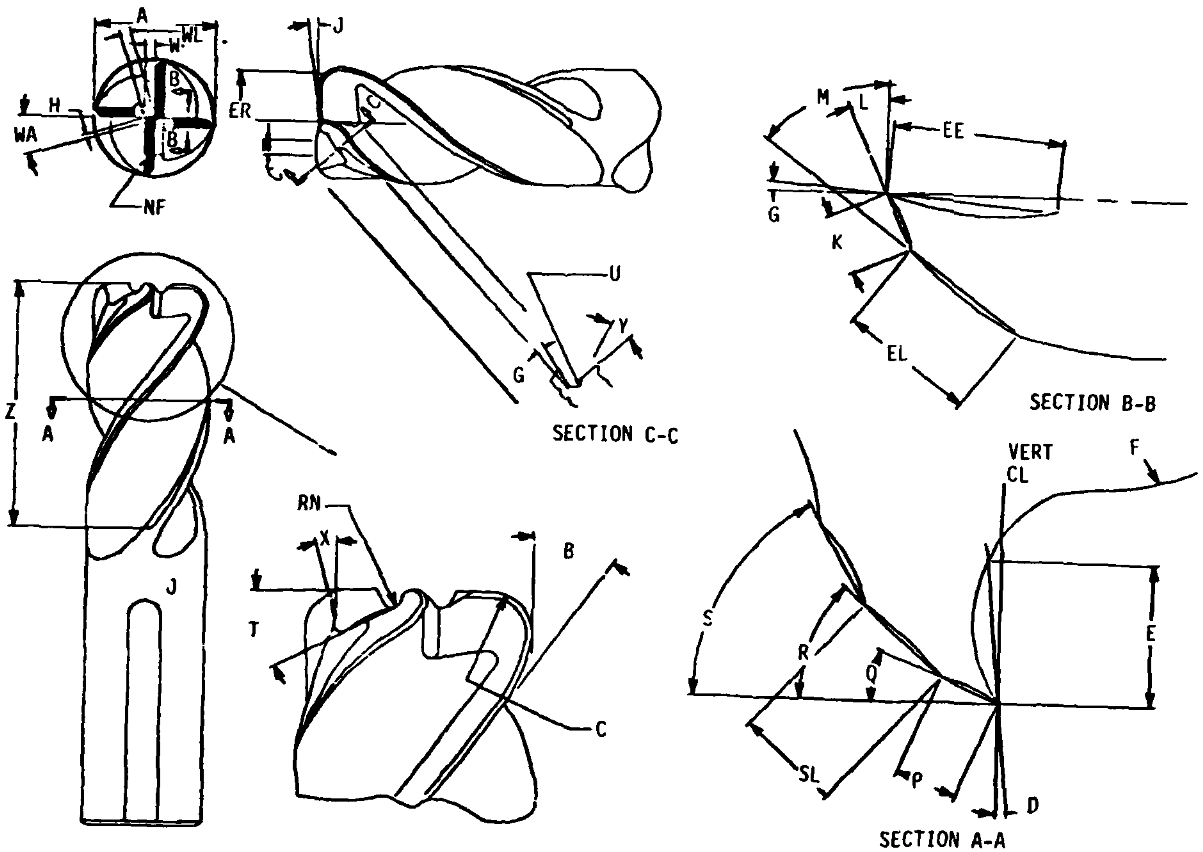

Figure 3A. Cutter Geometry.

	DESCRIPTION
A	CUTTER DIA (CDIA)
B	HELIX ANGLE (HELIX)
NF	NUMBER OF FLUTES (NFLUTE)
C	CORNER RADIUS (RAD)
D	RADIAL RAKE ANGLE (RAKE)
E	RAKE CHECK (RAKECK)
F	CORE DIA (COREDI)
G	AXIAL RAKE ANGLE (ARAKE)
H	DIAGONAL WEB THICKNESS (DWEB)
J	DISH ANGLE (EANG)
K	END PRIMARY LAND WIDTH (ELAND)
L	END PRIMARY CLEARANCE ANGLE (EPRI)
M	END SECONDARY CLEARANCE ANGLE (ESEC)
N	WIPER FLAT (WFLAT)
P	PRIMARY LAND WIDTH (PLAND)
Q	PRIMARY CLEARANCE ANGLE (PANG)
R	SECONDARY CLEARANCE ANGLE (SANG)
S	TERTIARY CLEARANCE ANGLE (TANG)
T	GASH ANGLE
U	GASH RADIUS
ER	EFFECTIVE CUTTING RAD
W	END GASH WIDTH
X	GASH BLEND (GBLEND)
Y	BOTTOM GASH ANGLE (BGA)
Z	FLUTE LENGTH (PLEN)

	FINISH
SL	SECONDARY LAND WIDTH
EL	END SECONDARY LAND WIDTH
EE	END RAKE CHECK
WA	WALK ANGLE
WL	WALK LENGTH
RN	NOTCH RADIUS

Figure 3B. Cutter Geometry Nomenclature.

PROGRAM DESCRIPTION

The two-phase program followed a systematic building-block approach to efficiently develop several key areas of the investigation. Figure 4 (pg 7) illustrates key milestones associated with these activities. These included:

1. Selecting the clearest opportunities for improving cutter life early in the program. Each concept was tested for short-term results. Some of these were rough and finish cutter material, rough and finish cutter stiffness, and wear allowance, cutter speed and chip thickness (feed rate) coupled with specific cutter geometries.

2. Utilizing expert consultants (including cutter manufacturers) to make certain that a broad base of cutter technology was reviewed to offer all worthwhile opportunities. Their suggestions were sought concerning cutter parameters and methods of testing. Key items considered were the number of cutting edges, cutting fluid, cutter rake angle, the depth of cut, and width of cut.

3. Investigating and testing new cutters using a substantial number of cutters having each of the key characteristics to be evaluated. Tests were conducted with production milling machines, as required. Tape trials were run on a developmental 5-axis 4-spindle miller and the final evaluation was conducted on a production 5-axis 4-spindle (Rigid) miller.

4. Utilizing an 8-axis CNC (Huffman) cutter grinder cutter geometry was modified to provide the best possible results consistent with production methods. NC programming was prepared, as needed, to make tests with larger diameter, stiffer cutters, with increased finish cutter wear allowances without increased airfoil thickness, and with different cut dimensions. Tests included inspecting each cutter before use, monitoring the wear and life during use, inspecting each cutter after use, and visually monitoring the machined surface texture and machined dimensions produced during tests.

5. Investigating new methods and equipment for inspecting cutter geometry, including automated inspection. The capability of each commercially available system was compared with the capability of the currently used methods and equipment. Inspection time, characteristics to be inspected, and precision were the main criteria. Capability was related to equipment cost and conclusions were drawn relative to the economic benefits of equipment procurement. An equipment specification was prepared.

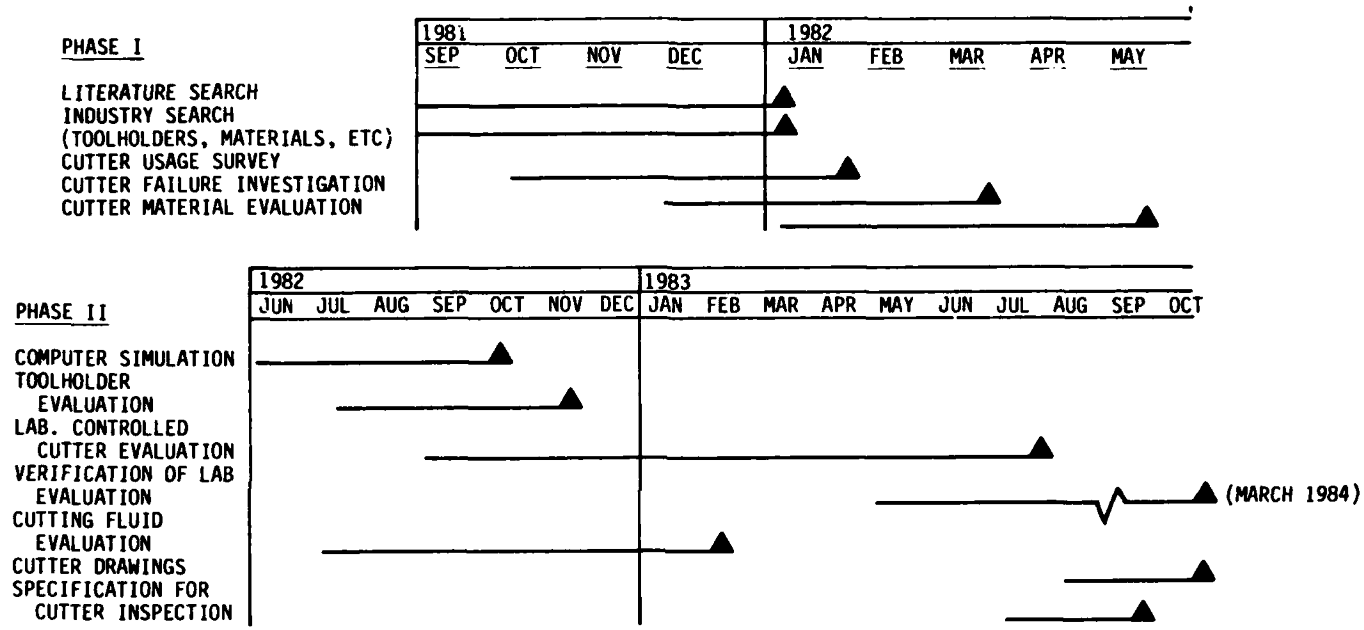

Figure 4. T700 Cutter Life Improvement Program - Major Milestones.

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PHASE I: INVESTIGATION OF CUTTER PARAMETERS

PHASE I: INVESTIGATION OF CUTTER PARAMETERS

The primary purpose of Phase I was to investigate cutter parameters that would reduce cutter usages. The major tasks of Phase I included a literature and industry search to understand and assess related efforts; a cutter usage survey; a cutter failure investigation to understand the magnitude and nature of the problem; and a cutter material evaluation.

LITERATURE SEARCH

A literature search was conducted to establish an understanding of new experimentation and techniques that were being conducted in industry and in the scientific community to evaluate cutters and cutter materials. Sources included text books, conference proceedings, industrial and technical journals. A complete list of references appears on pages 59-61.

The most beneficial result of the literature search was the development of a Cutter Failure/Cause Matrix for failed cutters. This evaluation capability, shown in Figure 5 (pg 10), represents a cross-referencing of cutter and machining parameters and their effect on cutter life. This evaluation capability has been a valuable asset, allowing identification of cutter failure causes and the means to eliminate them.

INDUSTRY SEARCH

Toolholders

In the industry search, numerous manufacturers' data sheets were scanned to obtain information on commercially available toolholders, cutting fluids, cutter materials, and surface coatings for cutters. This search revealed three types of toolholders: a solid-nose holder with set screw locking (as was being used in Hooksett); a single-angle collet toolholder; and a double-angle collet toolholder. All are shown in Figure 6 (pg 11).

Of the the three holders, the double-angle collet had the highest capacity range, followed closely by the single-angle collet. The solid-nose toolholders because special holders are necessary for each cutter shank diameter required a large inventory of toolholders.

Cutting Fluids

Several cutting fluid suppliers were consulted to determine if any of the standard oils or the new synthetic fluids or water-soluble fluids could be utilized during blisk and impeller manufacture to increase cutter life. Products from Castrol and Morcut, representative of current state-of-the-art cutting fluids, were recommended for evaluation.

LITERATURE SEARCH

CORRELATION MATRIX BETWEEN MACHINING PARAMETERS AND CUTTER FAILURE CAUSES

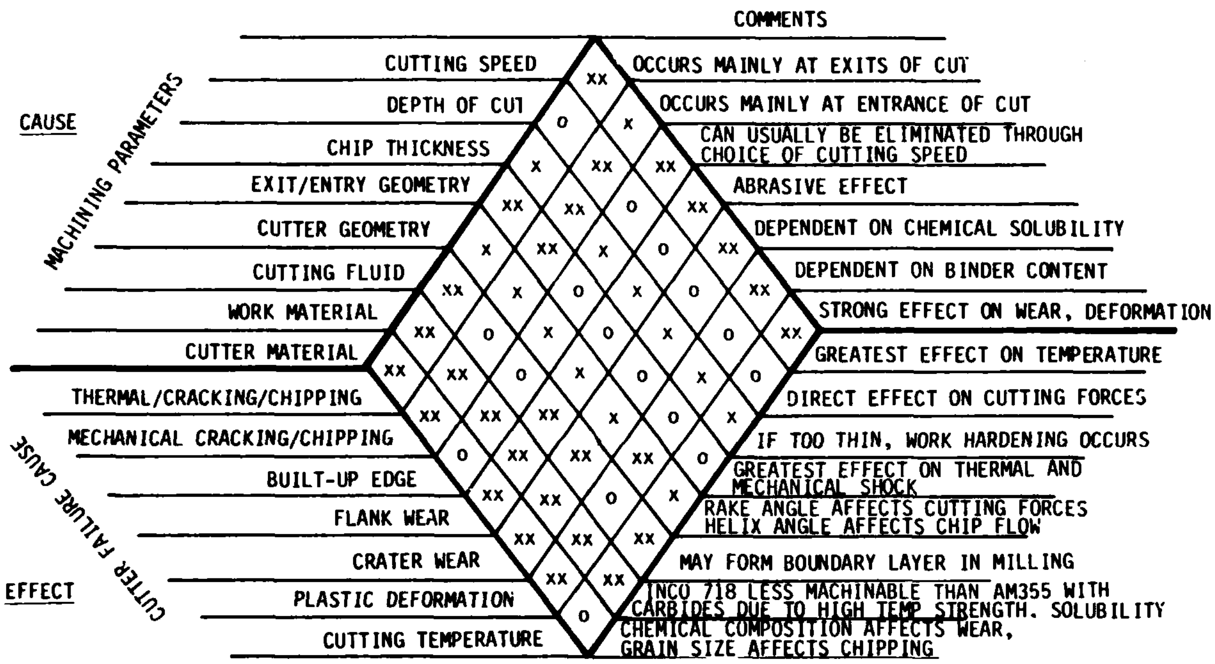


Figure 5. Correlation Matrix Between Machining Parameters and Cutter Failure Causes.

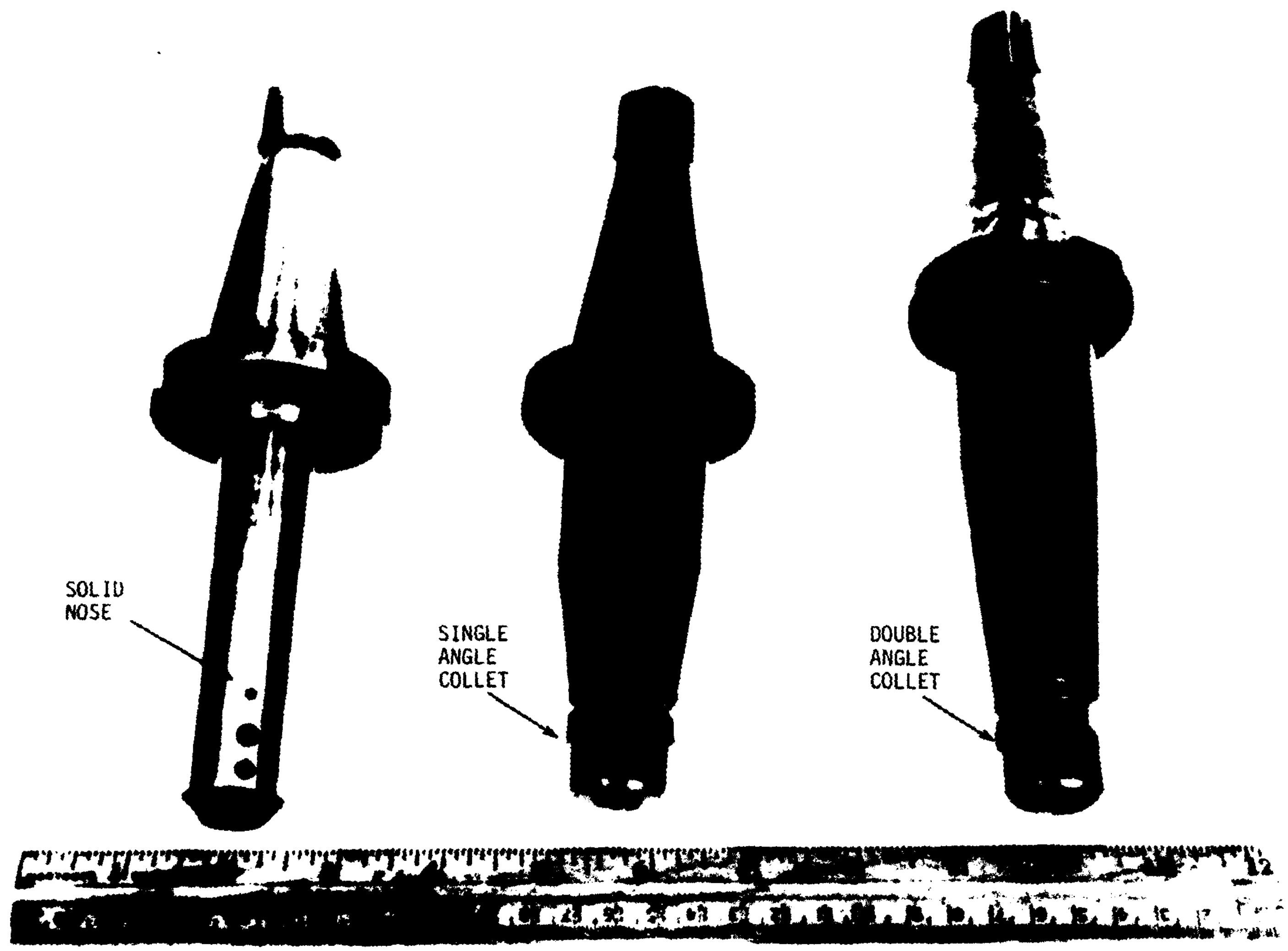


Figure 6. Typical Milling Toolholders Tested for Rigidity, Repeatability, Gripping Force, and Accuracy.

INDUSTRY SEARCH - Continued

Cutter Materials

The substantial difference in the machining of aerospace superalloys in comparison with the more conventional materials is evident when comparing the machinability indices of these materials. Inconel 718 (a nickel-based superalloy) is rated at 12; AM355 (an iron-based alloy) is rated at 38. By comparison, aluminum is rated at 200, and low carbon steel is rated at 100. A graphic comparison is shown in Figure 7 (pg 13).

The industry search revealed that no new carbide developments have been made for the machining of superalloys. Several manufacturers were consulted (Carboloy, VR Wesson, and Kennametal). All verified that grade C1, C2, C3 and C5 carbides were the most commonly used cutter materials for machining superalloys. Each recommended several of their grades for testing. All of these could be classifed into three distinct types of carbide; the micrograin (grain size less than 1 micron), straight tungsten carbide (tungsten carbide with cobalt), and complex carbides (straight tungsten carbides with other carbide additions). Those chosen for evaluation are shown in Table 1.

TABLE 1. CARBIDE CUTTER MATERIALS EVALUATED

Carbide Type	Grade
TUNGSTEN CARBIDE	
Walmet 110	C2
Kennametal K8735	C1
Carboloy 883 (Baseline)	C2
Kennametal K68	C2
MICROGRAIN	
Carboloy 820	C2
Carboloy 895	C3
VR/Wesson Ramet I	C2
COMPLEX	
Carboloy 370	C5
Carboloy 390	C5

Surface Coatings

New developments in physical vapor deposition (PVD) and chemical vapor deposition (CVD) techniques had opened up a new field of coated cutting tools. Coatings of Hafnium Carbide (HfC), titanium carbide (TiC), and titanium nitride (TiN) are common and were recommended for evaluation. Although not strongly recommended for cutting superalloys, especially in applications where numerous resharpenings of a cutting surface occurs, the chemical stability of these coatings at the expected cutting temperatures was attractive. Therefore, it was decided to evaluate coated cutters.

INDUSTRY SEARCH - Continued

Surface Treatments

Several steel cutting manufacturers (Gillette, Hamilton Standard, Texas Instruments) were demonstrating impressive results with cryogenically treated cutters. This low temperature treatment is a post-processing heat treatment with controlled cooling to -295°F, holding at -295°F, and then controlled heating to room temperature. This treatment takes retained austenite out of solution in high speed steel tooling, thereby increasing the tool's strength.

While there was no metallurgical reason to believe the process would perform in a similar manner with carbide tooling, there were claims that the process did indeed work with carbide cutters by reducing grain size. This process was also investigated.

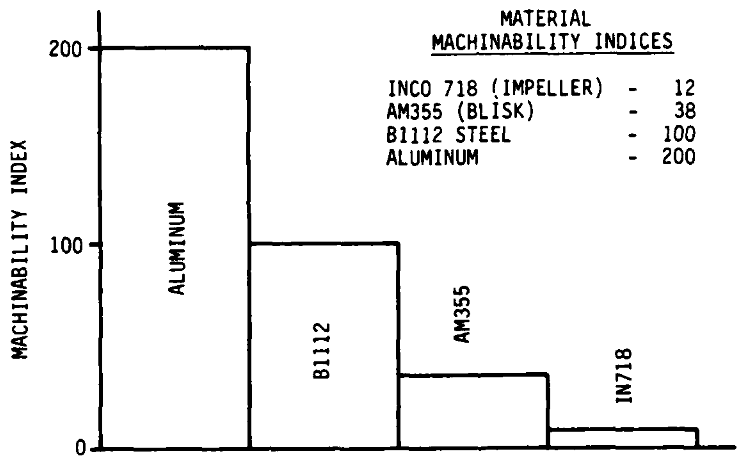


Figure 7. Relative Machinability of Blisk and Impeller Materials, Low Carbon Steel, and Aluminum.

LABORATORY TESTING

Toolholder Evaluation

Under production conditions, tools gripped in the solid-nose toolholders would often spin in the toolholder before failing. When the three holders were ranked for their gripping forces, the double-angle collet holder proved superior while the single-angle collet and solid-nose (if the cutter had a flat ground surface on the shank) were equal but slightly weaker than the double-angle collet.

The overall complexity of the toolholder was also investigated in order to determine if an alternative toolholder could be considered for use in a production environment. In this category, the simplest was obviously the solid-nose for its ease in changing cutters and toolholders with minimal effort. The single and double-angle collets became progressively more complex due to the required surface areas that must be kept clear of chips and other contaminants when assembling the cutter and toolholder into the machine.

Despite the flexibility of the solid-nose holders, tests were undertaken to determine if the added accuracy, increased capacity, and gripping force of a double-collet toolholder could be utilized to increase cutter life and provide a more accurate airfoil.

Laboratory testing of each of these toolholders involved determining their static deflection, ease of use, repeatability, and flexibility. Static loads were applied using the cable and weight system shown in Figure 8 (pg 15). Loads were applied at three points on each holder and the deflections measured with a dial indicator. The results are shown in Figure 9 (pg 16).

Flexibility and ease of use are subjective parameters; however, all operators querried agreed that the double-angle collets, though slightly more difficult to maintain, appeared to work consistently; providing a more repeatable airfoil.

A switch to the double-angle collet toolholders in a limited test case on the production floor showed an 11% improvement in cutter life and a thinner, more consistent airfoil. This was due to the increased rigidity of the cutter-toolholder system. A summary of the feature for these toolholders is shown in Table 2.

TABLE 2: SUMMARY OF TOOLHOLDER FEATURES

Type	Accuracy	Capacity Range	Gripping Force	Complexity
Solid-Nose with Set Screw	Decreases with Wear	One Diameter Only (Without Bushings)	High with Flat Ground on Tool	Simplest
Single-Angle Collet	High	Wide	High	More Complex
Double-Angle Collet	High	Widest	Higher than Single Angle	Most Complex

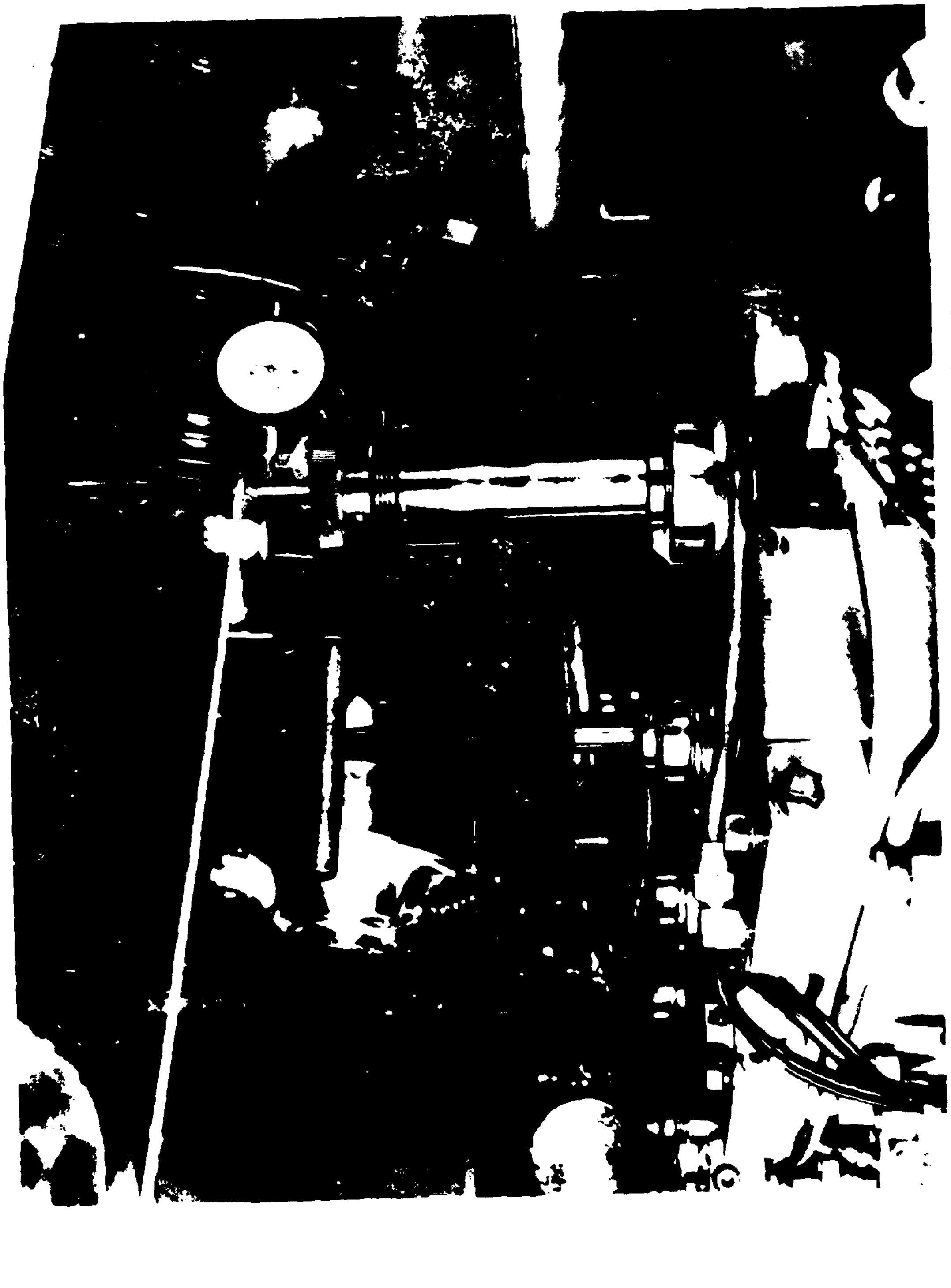


Figure 8. Toolholder Deflection Testing Equipment.

LABORATORY TESTING - Continued

The double-angle collets were then implemented through the shop and remain in production today.

It should be noted that since the rigidity of the toolholders was known to be of prime importance in reducing cutter eccentricity, tests were run to measure the maximum allowable size toolholder that could be used to cut each of the six components. Sketches (based on the clearance allowed by the machine, fixturing, part, and NC program) of "special" toolholders for each component were developed and are shown in Appendix A. These "special" toolholders were not implemented due to the difficulties in maintaining control over the setups, and risks of using an improper toolholder on a component.

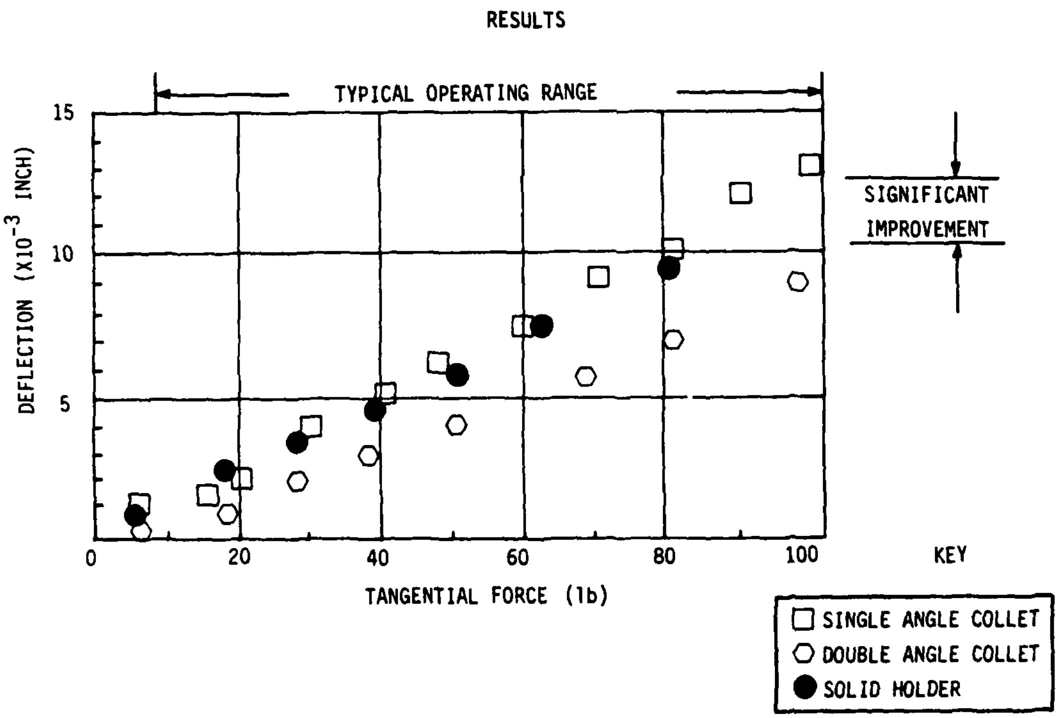


Figure 9. Deflection of Toolholders Under Static Loads.

CUTTER MATERIAL TREATMENT AND COATING EVALUATION

Selected Materials

The selected cutter materials in Table 1 (pg 12) were evaluated in the Lynn laboratory (see Figure 7, pg 13). The analysis of each material consisted of hardness testing, Kevex analysis, and metallographic evaluation for verification of a fully dense structure.

Photos of each sample were taken at 1500X as reference for grain size, structure, and to determine if impurities were present. The samples were then coated and tested for chemical composition on the Scanning Electron Microscope (SEM).

The Kevex analyzer was used to determine elemental composition of each sample. While quantitative analysis is difficult from the Kevex X-ray mapping, a qualitative understanding is obtainable. In the event of inconsistent material, the X-ray spectra will differ from the standard for that material.

It should be noted, however, that the cemented carbide materials tested are sintered products. Therefore, while composition could be within specification, if the sintering cycle were not complete or varied from the cycle used on the standard, an inferior cutting material could result. This would not be identified in a Kevex analysis.

To remedy this, throughout the later stages of Phase II when the material in question was not performing to the norm, a coercive force analysis was done on the material. This test utilizes sensitive transducers to measure the amount of energy required to demagnetize a sample. The energy is indicative not only of composition, but of the degree of sinter (density) as well.

Once the quality of the carbide was assured, several cutters were ground to the baseline Hooksett geometry. Each cutter was inspected, then used to machine both impellers and blisks. After removing identical amounts of material, each cutter was checked for chipping and wear. Of the grades tested in the laboratory, Carboloy 883, 895 and Walmet 110 were superior. These grades were recommended for further testing in Phase II.

Surface Coatings

Where the chemical interaction between the cutter and workpiece material is the primary wear mechanism, coating of the cutter is recommended. Chemical wear, the diffusion of the cutter material into the chip, is greatly accelerated by the high temperature and pressure seen at the cutter tip. At elevated temperatures, the activity of each material is increased. As the chip from the workpiece travels across the cutter face, small particles of the cutter attach to the chip and are carried away. This wear mechanism can be controlled by reducing the affinity of the cutter material for the workpiece. This is often done by coating the cutter.

CUTTER MATERIAL TREATMENT AND COATING EVALUATION - Continued

In the case of cemented carbides, a more brittle yet more chemically stable coating of HfC, TiC, or TiN is deposited on the cutter through either PVD or CVD techniques. This composite cutter maintains the toughness of a cemented carbide cutter, yet adds the high hardness and highly wear resistant chemical stability of a HfC, TiC or TiN tool. This coating ranges from a few hundred angstroms to several millimeters thick.

In tests performed with HfC, TiC and TiN coated Grade 883 cutters, the coated cutters showed no change in cutter life in blisk and impeller milling. Coating delamination and burning were the primary problems. This, coupled with the fact that resharpening the tooling gradually removed the coating led to the conclusion that the added expense of coating cutters could not be justified.

Surface Treatments

To evaluate cryogenic treatments, Carboloy 883 carbide milling cutters were cryogenically treated and evaluated in a comparison test with untreated cutters on AM355. In all cases, no significant change in cutter life was seen between the treated and untreated cutters.

CUTTER USAGE SURVEY

A cutter usage survey was conducted at Hooksett to determine the number of cutters being used for each component of the compressor section, and to determine the percentage of roughing, finishing, and platform cutters used in each component. A cutter was considered used if it failed, or developed a wearland in excess of 0.012 inch. A typical survey form is shown in Figure 10 (pg 19).

The results of this survey, shown in Figure 11 (pg 20) indicated that 62% of the cutters used to produce the T700 compressor rotor components were being used in producing the impeller. The three roughing cutters constituted 50% of the total usages.

CUTTER FAILURE INVESTIGATION

In order to determine the most effective changes in cutter geometry and cutter material, a study of tool failure was undertaken.

Cutter breakage was very high at 11%. Breakage is of special concern since fragments of carbide may become permanently imbedded, or gouge the parts to the point of scrapping the part. NC programming of 5-axis milling is indeed complex and calculating chiploads is extremely difficult, however, since the tape location of the cutter failures had been recorded in the survey, the high cutter breakage areas and the NC program location were correlated. Corrective programming and reduced chiploads via speed-feed changes were applied immediately and showed a 4% increase in cutter life and a 7% reduction in breakage (Reference 38). Breakage also prevents reuse through resharpening, thus increasing costs.

Several cutters were removed from Hooksett when catastrophic failure occurred to that tool. They were returned to the Lynn laboratory for an analysis of the material and a detailed examination to determine the mode and cause of failure.

DATE: ______________
OPERATOR: ______________

PART: STAGE 1 STAGE 2 STAGE 3 AND STAGE 4 STAGE 5 IMPELLER

TYPE OF CUTTER: 5/16 R

POCKET/OPERATION	NUMBER OF POCKETS	FAILED	NC TAPE LOCATION AT FAILURE
C	6	X	

Figure 10. Cutter Usage Survey Form.

CUTTER FAILURE INVESTIGATION - Continued

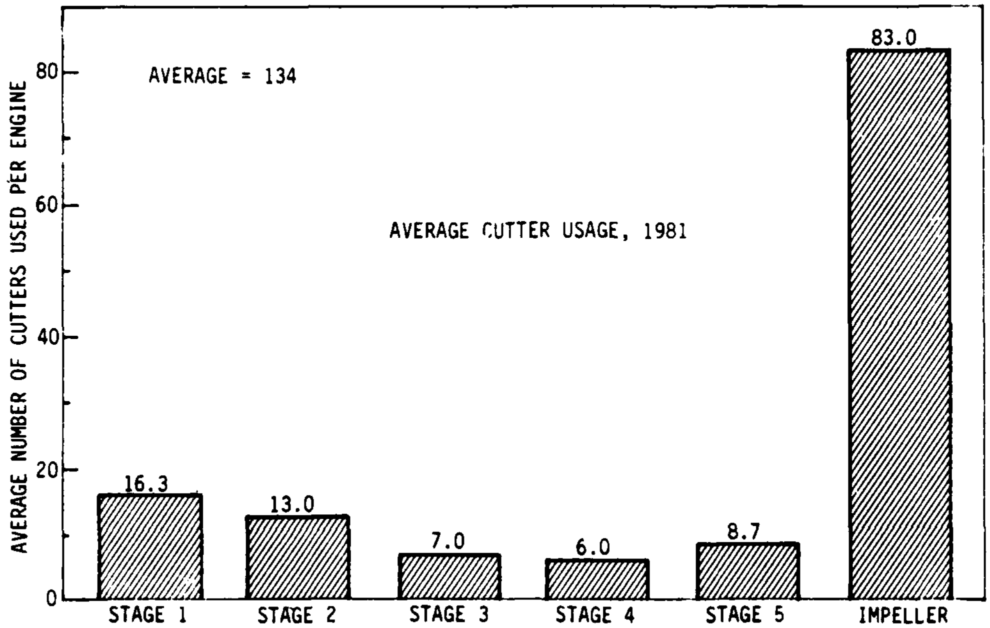


Figure 11. Cutter Uage Survey Results, 1981.

Analysis

The milling cutters, shown in Figure 12 (pg 23) were part of a sampling of cutters that failed in production. A preliminary analysis of the cutter material showed no significant difference between the failed cutter materials and the specification for 883 carbide, as evidenced by Figure 13 (pg 24), the Kevex spectrograph for 883 carbide.

Analysis of the failed cutters have shown that excessive torque generated by a blunted cutting edge led to torsional failure of the cutters (Reference 35). Causes of the blunted edge (i.e. excessive primary wearland as shown in Table 3, pg 21) are continued usage beyond the useful life of the cutter, improper cutter materials, lack of chip clearance in the cutter, improper cutting speed, or improper feed rate. Excessive chipping, caused by using a low toughness grade cutter, was not as prevalent as one would expect based on the interrupted milling action and the difficulties of machining these superalloys. Other evidence such as irregular flute wear (runnout) and surface oxidation (improper cooling) were found in only a few samples.

Accurately knowing the material composition and the cutting conditions allowed the cause to be pinpointed to improper cutting parameters and cutter geometry. In addition, it was also noted that, for the given production application, flute length was excessive, thereby further weakening the cutter.

CUTTER FAILURE INVESTIGATION - Continued

The Huffman 8-axis CNC cutter grinder was used to modify cutters on a limited basis to verify these findings. Modifications to the cutters were made by increasing the following:

Primary Land	.002 inch to .005 inch
G-blend	45° to 90°
Secondary Clearance Angle	20° to 40°
Primary Angle	6° to 8°

The result of testing these cutters showed improved chip removal from the cut due to increased primary and secondary clearance angles; a smoother blend between the side and end of the cutter due to the increased G-blend and a stronger cutter due to an increased primary land width; thereby improving cutter life.

As a result of examining the cutters both before and after cutting, several quality problems on incoming cutters were identified and recommended for further evaluation. These included improving the surface finish of primary grinds in order to reduce sharp discontinuities on the cutting surface.

These changes were implemented in Hooksett during Phase I. Additional work to optimize the cutter geometry was recommended for Phase II.

TABLE 3. CUTTER WEARLANDS

Cutter No.	Diameter (In.)	Wearland on Corner (inch) Flute No. 1	2	3	4	5	6
1	.250	.010	.014	.015	.010	.012	.011
2	.312	.011	.011	.010	-	-	-
3	.312	.010	.009	.010	-	-	.009
4	.312	.014	.017	.020	.013	.014	.013
5	.312	.017	.016	.013	.015	.013	.017
6	.187	.015	.017	.017	.019	4 Fluted	
7	.187	.010	.014	.013	.011	4 Fluted	

PHASE I SUMMARY AND RECOMMENDATIONS

In May 1982, Phase I of the T700 Cutter Improvement Program was completed. An extensive literature search had led to the development of a cutter failure matrix relating cutting parameters to cutter failure modes and potential solutions. A study of cutter usage and the Hooksett milling practice was performed, identifying high usage areas and probable causes of cutter failures.

Investigation of state-of-the-art toolholders had revealed a more accurate, more rigid double-angle collet toolholder. After examining test results from the lab evaluation and limited production verification, the toolholders were implemented in Hooksett. Implementation of double-angle toolholder showed an 11% reduction in cutter usage.

A cutter failure analysis survey led to the isolation of deficiencies in the NC programs used for milling. These deficiencies were eliminated and cutter usage dropped an additional 4%.

Several grades of carbide from tooling manufacturers were chosen and evaluated. From these preliminary tests; three grades (Carboloy 883, 895 and Walmet 110) were recommended for further evaluation and for extensive study of parameter effects (speeds, feeds, and geometry modifications) on cutter life.

Coatings of TiC, TiN and HfC were tested; however they proved to be ineffective for extending cutter life due to their excessive chipping and delamination.

Cryogenic treatment of carbide tools showed no improvement in cutter performance.

Cutters with increased primary and secondary clearance angles, land width, and G-blend showed improved cutter life in the laboratory and in a controlled evaluation in the production environment. These changes were implemented under Phase I.

After completing Phase I, implementation of the results showed a 15% reduction in cutter usage. Additional means to extend tool life were revealed in Phase I and recommended for evaluation in Phase II of the T700 Cutter Life Improvement Program. Funding for Phase II, Optimization and Verification of Cutter Design was awarded.

SHANK FAILURES

FLUTE FAILURES

Figure 12. Examples of Cutter Failures in Production.

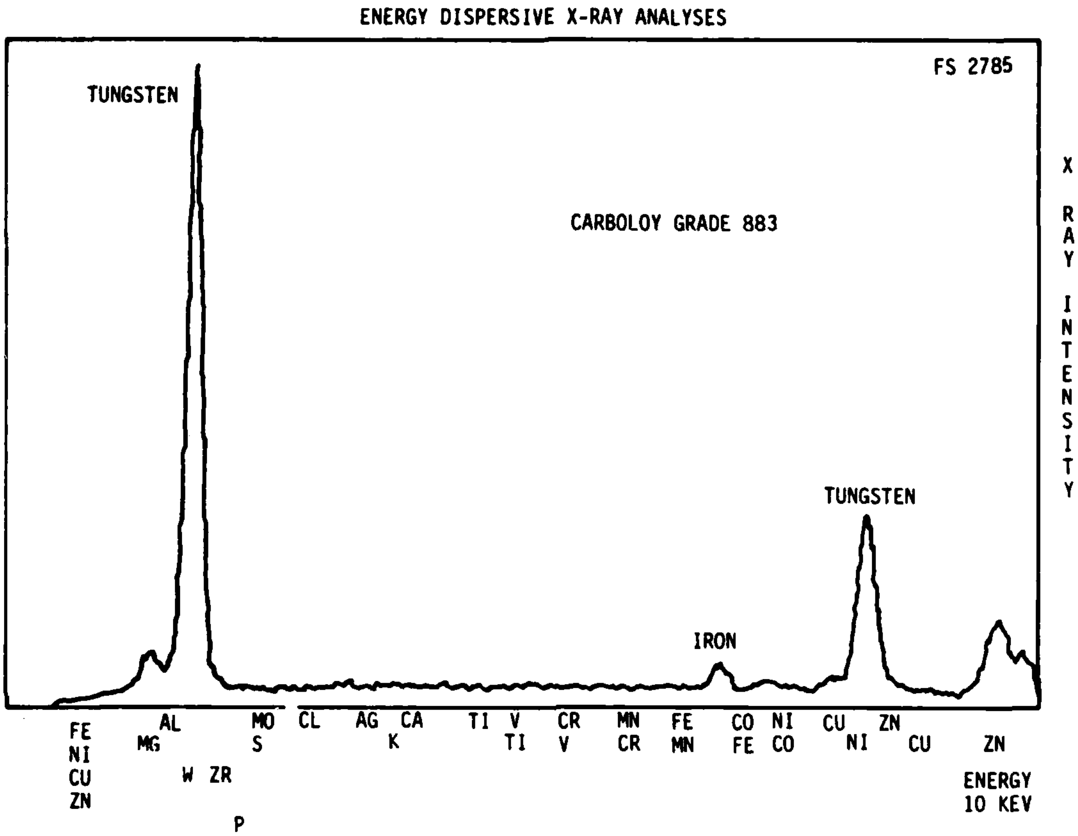


Figure 13. Typical Kevex Spectrograph - Carboloy Grade 883 Carbide.

PHASE II: OPTIMIZATION AND VERTIFICATION OF IMPROVED CUTTER DESIGN

PHASE II: OPTIMIZATION AND VERIFICATION OF IMPROVED CUTTER DESIGN

Successful completion of Phase I of the T700 Cutter Life Improvement Program led to a 15% reduction in cutter usage and associated cutter change costs. Reductions were a result of increasing the rigidity of the toolholders, identifying and correcting isolated problem areas in the NC tapes.

COMPUTER SIMULATION OF THE MILLING PROCESS (See Reference 37)

This section covers the work done on a computer model for the end-milling process. It describes the features of the model, the results of modeling blisk and impeller milling, and some conclusions and recommendations.

Features of the Model

This computer model (see Milling Simulation program listing in Appendix B) is for peripheral end milling where the spindle and cutter compliance is significant. The model permits studying the effects of a great many variables including stiffness, eccentricity, cutter geometry, etc. The list of variables, and their initial values, is given in Table 4.

TABLE 4. CUTTER COMPUTER SIMULATION VARIABLES

	CUTTER DATA	
	NOTE:	
1.	Number of Teeth	N1 = 6
2.	Cutter Radius, inches	R1 = 5/32
3.	Cutter Overhang, inches	L1 = 2
4.	Rake Angle, degrees	A1 = 0
5.	Relief Angle, degrees	G1 = 6
6.	Initial Radial Wear, inches	R3 = 0
7.	Cutter modulus,psi	E1 = $94*10^6$
8.	Transverse Rupture Strength, psi	S1 = 290,000
9.	Thermal Conductivity, lb/sec/°F	K9 = 13
10.	Volumetric Specific Heat, lb/in^2/°F	C9 = 210
11.	Failure Wearland, inches	W9 = .005
12.	Wearland Thermal Activation Energy, cal/mole	Q9 = 40,000
13.	Diffusion Wear Constant, inches/sec.	D9 = 5000
	WORKPIECE DATA AM355	
14.	Brinell Hardness Number	H = 350
15.	Specific Energy at T = .01 inch	U9 = 500,000
16.	Effective "friction angle", degree	B = 45
17.	Spindle Speed, rpm	N = 2760
18.	Feed Rate, inches/min.	F = 4.2
19.	Width of Cut (radial depth), inch	W = .3125
20.	Axial Depth (alter in program), inch	D = .06
21.	Spindle Stiffness, lb/inch	K = 25,000
22.	Spindle/Tool Eccentricity (Tooth 1), inch	E = 0
23.	Mean Radial Tooth Error, inch	R2 = 0
24.	Increments per Revolution	N2 = 24

COMPUTER SIMULATION OF THE MILLING PROCESS - Continued

Figure 14 shows the cutter geometry. The cutter rotates in a counterclockwise direction, and moves (relative to the work) in the +y direction. A positive force, Fx, acting on the tool, will move the cutter to the right. Fy is usually negative, producing bending of the cutter in the -y direction.

The axial depth of cut can be varied with angular position. For the data to follow, the depth was 0.12 inch for the first 90 degrees and 0.06 inch for the remainder.

Regarding dynamics, the natural frequency of the cutter itself is much higher than the various cutting frequencies. It is assumed, therefore, that the cutter will always be in an equilibrium location. If any machine-spindle resonances are near the cutting frequencies, this will not be true.

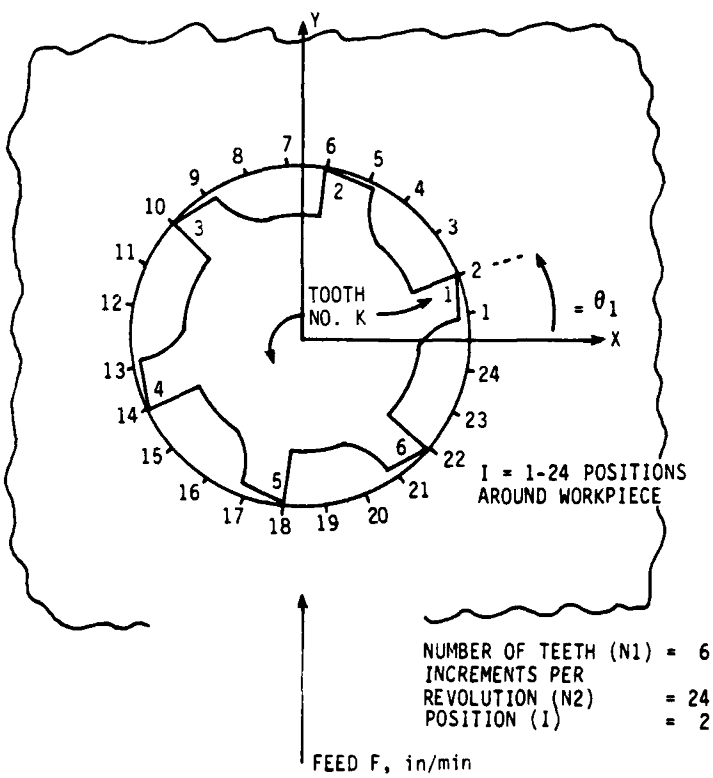


Figure 14. Cutter and Work Geometry Used in this Simulation.

COMPUTER SIMULATION OF THE MILLING PROCESS - Continued

In operation, the program maintains a record of the workpiece shape due to the most recent passage of a flute that removed a chip.

For each increment of cutter rotation, the program iterates to determine the cutter position where the total force on the cutter and the resulting cutter deflection are consistent (within an iteration error E9 = 0.000005 inch). When the total stiffness is high, no iterative steps are required; however, when the stiffness is low (as actually measured) many iterations (50-100) may be required to determine the equilibrium position.

Hence, when the stiffness is low, the program is correspondingly slow in execution; each increment of angle requires many iterations, and a number of revolutions are required before the cut settles down to a "steady-state" periodic condition. Sometimes 4-5 hours are required. Fortunately, the programs are run on a personal computer (North Star) so that the program can run all night with no attention (or cost).

In addition to computing the cutting force on each flute (including a "size-effect"), the force on the wearland is added. The temperature at each flute, and the resulting wear is also estimated. These force-temperature-wear estimates are based on analytic treatments described in "Manufacturing Analysis" (Reference 31).

The program will indicate failure whenever the limiting wearland or the cutter fracture stress is reached.

Results

Verification

It is difficult to verify a program such as this to determine if it is operating properly. Two methods of verification are:

1. Run a simple set of conditions that can be verified by hand.

2. Run a set of conditions where experimenatal data are available.

Both have been done, and (at least for forces where data are available) the program performs satisfactorly.

Magnitude of Forces

Perhaps the most important result concerns the size of the predicted forces as compared to those that were measured. While the predicted maximum forces for a new cutter are less than 100 pounds, forces in excess of 200 pounds were measured.

Either the cutting mechanism for this material is quite different than originally anticipated, or there are additional forces, presumably from cutter interference (lack of clearance). Evaluation of worn cutters have shown the latter.

COMPUTER SIMULATION OF THE MILLING PROCESS - Continued

Stiffness-Eccentricity Tradeoff

In any production milling operation, there is bound to be cutter run-out or eccentricity. For the case at hand, when the effects of the spindle, the toolholder, and the cutter itself are considered, eccentricity of the order of 0.001 inches can be expected under "good" conditions.

Eccentricity generally gives rise to higher cutting forces because some of the flutes must take larger chips. Here, where cutter breakage is to be avoided, minimizing the maximum force as seen by the cutter is beneficial, i.e., minimizing eccentricity is imperative.

Because accuracy of the cut is also important, the elastic deflection of the tool from its nominal position is also to be limited; i.e., a high cutter-spindle stiffness is preferred.

Figure 15 (pg 29) shows the transverse force, Fx, for one revolution of a stiff (K2 = 1,000,000 lb/in.) cutter-spindle. Curves for zero eccentricity and 0.001 inch eccentricity are shown. The peak value of Fx is approximately 250% larger with 0.001 inch eccentricity.

Figure 16 (pg 29) shows comparable data for a system of low stiffness (K2 = 20,000 lb/in.). Here, the peak Fx is increased only 40% by the same eccentricity.

It is expected that the cutter compliance would compensate to some degree for eccentricity. Now quantitative measures for that compensation can be made. Figure 17 (pg 30) shows how the peak total force (resultant of Fx and Fy) varies with stiffness and eccentricity.

In the simulation, and as expected in actual cutting, the eccentric cutter tends to deflect toward the "center" of the cut to more evenly distribute the chip load between the cutter teeth. However while the geometry of the parts is only slightly affected; the life of the cutter, due to fatigue, is greatly reduced. Therefore, high cutter-spindle stiffness is desired. Eccentricity should be minimized to increase cutter life.

Conclusions

At this point, there are two avenues to pursue:

1. Using the model, consider the effects of varying feed and number of flutes.

2. If the forces, without interference, are as large as measured, consider the use of "sharper" tools; i.e., high speed steel, or micrograin carbides.

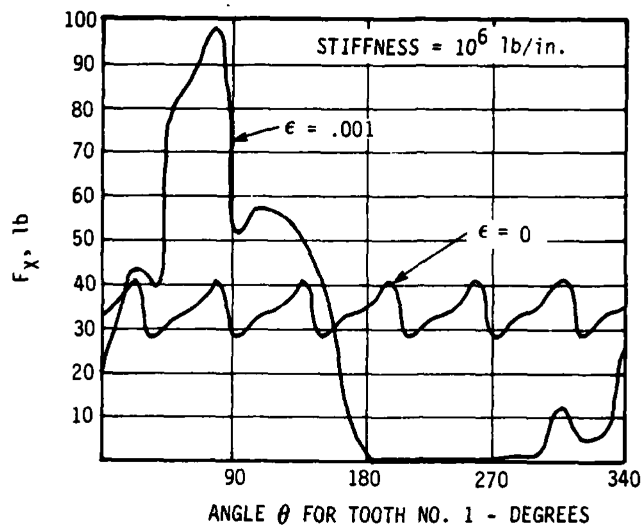


Figure 15. Effects of Eccentricity on Radial Cutting Forces (Stiffness = 1,000,000 lb/in.).

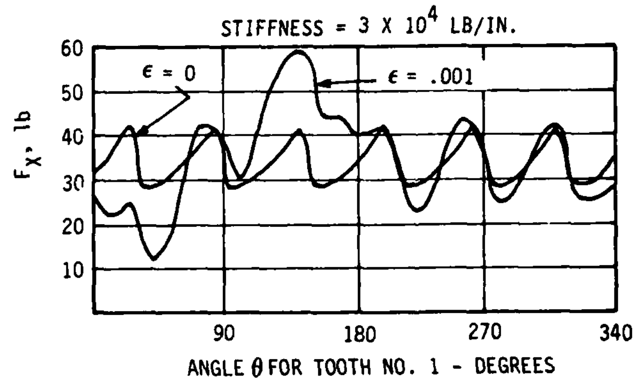


Figure 16. Effects of Eccentricity on Radial Cutting Forces (Stiffness = 20,000 lb/in.)

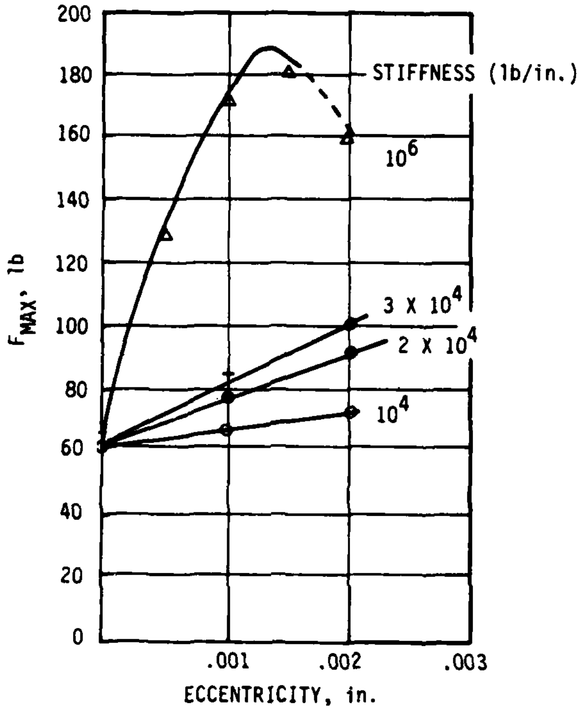


Figure 17. Effect of Stiffness and Eccentricity on Peak Resultant Forces During Cutting.

COMPUTER SIMULATION OF THE MILLING PROCESS - Continued

As a result of this simulation, micrograin carbides were chosen for further evaluation.

Geometry changes, increased primary land and increased primary and secondary rake angles, were evaluated in an attempt to reduce interference at the cutting edge.

CUTTING FLUID EVALUATION

With the recent developments of lubricants and new chemical additives (all promising increased cutter life) an evaluation of the cutting fluids selected from the Phase I study was also completed. Cutting fluids are introduced into the cutter-work interface to cool, lubricate, and also protect the part and machine from corrosion. Criteria for evaluating a coolant may be sump life, appearance, operator acceptance, safety, and obviously, cutter life.

Analysis

The evaluation looked at cutter life as the primary criteria; however, sump life, operator acceptance, and safety would not be sacrificed.

The coolants chosen for this study were Morekut 916, Castrol 910, and Castrol 958. Morekut 916, the baseline, is a heavy black sulfochlorinated oil. Castrol 910 and 958 are both translucent chlorinated oils, with the latter being of a higher viscosity and of greater high temperature stability. A single Rigid milling machine at the Hooksett plant was charged and maintained with each of the coolants for a period of one to two months. During this time, the cutter usage for each machine was monitored. During this evaluation, the coolants were monitored for proper concentration and adjusted if necessary. A summary of the cutter wear is shown in Appendix C, Cutting Fluid Evaluation Data.

Results

During the testing, the Castrol 910 fluid was removed from the experiment. A severe chemical reaction with several seals in the machine, traced to the coolant, caused destruction of the seals and necessitated a major repair.

Overall, a comparison of milling cutter usage for all the compressor components showed no major difference between Castrol 958 and Morekut 916. However, operators seemed to prefer the more translucent Castrol 958 for the purpose of observing the cutter.

When the data is analyzed on a part-by-part basis, cutter usage with Morekut 916 does show lower usage in the finishing of the impeller. No other parts showed a significant usage difference, and as such, changeover costs could not be justified. Hooksett has continued with the baseline, Morekut 916.

LABORATORY CONTROLLED CUTTER EVALUATION PROGRAM

Analysis of failed cutters from the blisk and impeller milling operations completed in Phase I concluded that cutter life could be extended by developing better cutter geometries and materials. With an infinite number of potential geometries and several tool materials available, a statistically designed Laboratory Controlled Cutter Evaluation was developed to reduce potential combinations to a minimum, yet valid, sampling. Of the recommended materials from Phase I, Carboloy 883, 895, and Walmet 110; the latter two were not readily available for testing. In light of the computer simulation and material availability, Carboloy 44A, a micrograin was substituted for Carboloy 895 and Ramet I was substituted for Walmet 110 due to availability.

Program Design

Statistical analysts were employed to reduce the miriad of candidate cutters to a workable sampling. With their assistance, a 3-3-2-2 factorial analysis was developed to randomly test the cutters. The Laboratory Controlled Cutter Evaluation is shown in Figure 18 (pg 33) and its components are listed in Table 5 (pg 34).

The Laboratory Controlled Cutter Evaluation represents a combination of three cutter diameters, three cutter materials, two cutter geometries, and two feeds. The cutters chosen for the test represented the three highest usage tools, the 5/16, 1/4, and 3/16 inch diameter roughing cutters. These three tools are used in roughing all of the T700 compressor components. For the laboratory test, the cutters were evaluated after milling pockets on the impeller, an IN718 forging.

The cutter geometries chosen for the Laboratory Controlled Cutter Evaluations were designed from the actual production cutters with modifications made to reduce flute length, improve grinding blend, and increase chip clearance.

The modified geometry was run with the baseline geometry in the Laboratory Controlled Cutter Evaluation. Feeds for the evaluation were chosen as a result of the failure analysis investigation and computer simulation. It was believed that an increased chip load would potentially reduce rubbing and abrasive wear since each cutting flute would be cutting under the work-hardened surface. Therefore the baseline feed rate and an increased feed rate were chosen. A comparison of the Huffman grind parameters for these cutters is shown in Table 6 (pg 35).

The Laboratory Controlled Cutter Evaluation was designed for, and carried out on actual T700 impeller forgings utilizing the same NC tapes used in production. To eliminate variation from spindle-to-spindle, only one spindle of the New England 4-spindle five-axis milling machine was utilized. The New England milling machine was controlled by a General Electric 1050 controller with both CNC and DNC capability. Both the CNC and DNC capabilities were utilized during these tests. Cutting fluid was applied to the cutter and cutting surface with dual nozzles to increase coolant flow to the cutter.

	TOOL	T1						T2						T3					
	MATERIAL	M1		M2		M3		M1		M2		M3		M1		M2		M3	
	GEOMETRY	G1	G2	G1	G2	G1	G2	G1	G2	G1	G2	G1	G2	G1	G2	G1	G2	G1	G2
CHIPLOAD	F1																		
	F2																		

Figure 18. Laboratory Controlled Cutter Evaluation.

TABLE 5. LABORATORY CONTROLLED CUTTER EVALUATION COMPONENT VARIABLES

CUTTER TYPES			CUTTER MATERIALS		
Cutter Code	Dia. (in.)	Use	Material Code	Name	Type
- T1	5/16	Roughing Cutter	- M1	Carboloy Grade 883	Baseline
- T2	1/4	Roughing Cutter	- M2	VR Wesson Ramet 1	Micrograin
- T3	3/16	Roughing Cutter	- M3	Carboloy Grade 44A	Large Grain

CUTTER GEOMETRY

Cutter Code	G1	G2	Comment
- T1	Baseline*	4-Flute	Increased primary land width. Increased primary and secondary clearance angles. "O" G-blend improved rake face grind at nose radius. Reduced flute length.
- T2	Baseline*	4-Flute	(Same as above).
- T3	Baseline*	2-Flute	(Same as above).

CHIP LOAD

Feed Code		Feed (in./min)/Speed (surface feet/min)		
		T1	T2	T3
- F1	Baseline	1.8/45	1.8/150	1.2/147
- F2		3.6/45	2.4/75	2.4/75

* Baseline conditions are detailed in Table 6 (pg. 35) and refer to the cutter geometry in use in Hooksett as of the start of Phase II.

TABLE 6. LABORATORY CONTROLLED CUTTER EVALUATION - GEOMETRY COMPARISON

	Tool I		Tool II		Tool III	
	I	II	I	II	I	II
End Parameters						
* NFLUTE	6	4	6	4	4	2
Flute Parameters						
FPEXIT	-	0.002	-	0.002	0.005	0.006
* PLEN	0.700	0.300	0.700	0.300	0.400	0.300
POLDP	-	-	0.045	0.040	0.050	0.041
End Parameters						
EANG	-	-	-	-	3.000	-
* ELAND	0.005	0.012	0.005	0.010	0.003	0.010
EPRI	-	-	-	-	12.00	8.000
ESEC	40.00	20.00	40.00	30.00	40.00	30.00
Gash Parameters						
ANOTCH	-	-	-	-	1.000	45.00
AEXIT	-	-	-	-	1.000	45.00
BGA	45.00	30.00	-	-	45.00	40.00
BGF	10.00	8.000	10.00	8.000	7.000	8.000
CEDIA	-	-	-	-	-	-
COREDIA	0.140	0.199	0.140	0.160	-	-
DWEB	0.015	-	0.010	0.160	-	-
GASH	-	35.00	40.00	30.00	40.00	35.00
* GBLEND	90.00	-	90.00	-	90.00	-
GRAD	-	0.010	-	-	-	-
HWEB	-	-	-	-	-	0.010
OFFNCH	-	10.00	-	10.00	-	10.00
RNOTCH	-	0.050	-	0.050	-	0.050
WCRAD	-	-	-	-	0.020	0.010
WLKANG	-	-	60.00	30.00	45.00	40.00
WLDLEN	-	-	0.010	0.015	0.020	0.010
WNOTCH	-	0.050	-	0.050	-	0.030
Diameter and Radius Parameters						
* FLEN	0.600	0.300	0.600	0.300	0.400	0.300
PLAND	0.005	0.012	0.005	0.010	0.005	0.010
SANG	35.00	20.00	35.00	25.00	40.00	24.00
SLANG	-	-	-	-	0.010	-
TANG	-	-		-	30.00	-

*Key Parameters

LABORATORY CONTROLLED CUTTER EVALUATION PROGRAM - Continued

Cutter Manufacture

Each cutter for this test was individually ground from carbide rod cut to 4-inch lengths. The rods were centerless ground on a TG/2x4 Royal Master Centerless grinder and then ground on a Huffman 8-axis CNC cutter grinder. The diameter, material, and geometry were coded onto the cutter shanks.

Testing

After grinding and prior to cutting, each cutter was inspected for consistency of land grind. The data representing the primary width of each flute was recorded.

Inspection of the cutter was carried out at approximately 50X magnification on a Dynascope equipped with fiber optic lighting for increased contrast. Descriptive photographs of typical cutters were taken using a Polaroid single frame camera and Polaroid 107 black and white film to clarify inspection terminology. Typical photographs and descriptions are shown in Figure 19 (pg 37). The cutters were installed in the toolholder, gaged for length, and then attached to the spindles. Next, the cutters were used to machine one pocket in the impeller. The 5/16-inch cutters were used to cut the "C" pocket, the 1/4 inch cutters were used to cut the "F1" pockets, and the 3/16 inch cutters were used to cut the "F2" pockets. Figure 20 (pg 38) shows the location of each lettered pocket on the impeller.

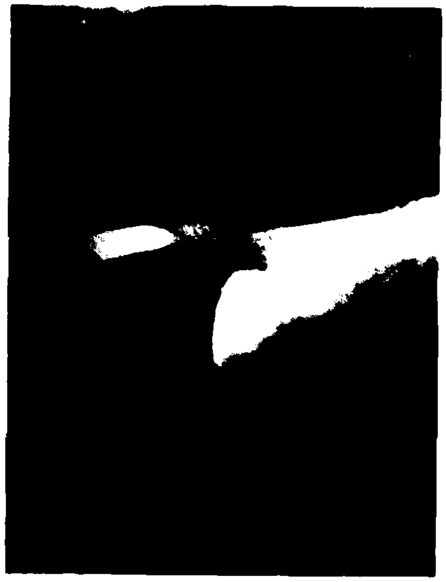
After one pocket was cut from the impeller forging, the cutter was removed and inspected. The flute wear (primary land width) and flute chipping was recorded. Again descriptive photographs of typical geometries (Figure 21, pg 39), typical of cutter condition after cutting, were taken for reference.

A second pocket of material was cut from the impeller forging using each cutter material. Again inspection of the cutter occurred after the second pocket was cut. Measurement of the primary land width and chipping were recorded.

This was repeated for the entire 72 cutters in the cutter evaluation. This data was then entered into data files on a Honeywell computer. The analysis of the data was performed by Charles Anton, statistical analyst, at General Electric, Lynn.

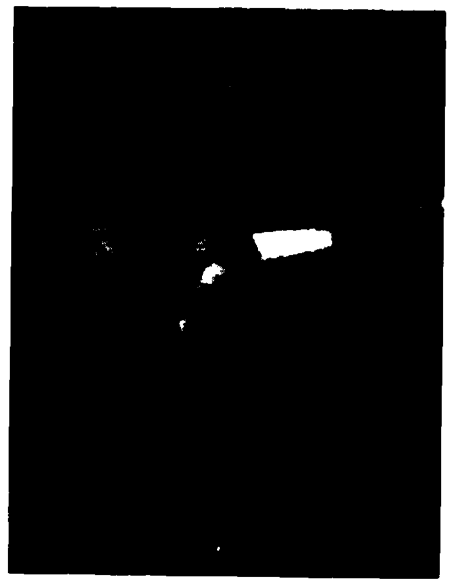
Results

Several alternatives existed on how to interpret the wear data from the statistical tests. What constitutes the longest wearing cutter? Was it the cutter with the least amount of total flute wear? The cutter with the least amount of average flute wear? Or the one with the fewest chipped flutes? All are important and each could be used to evaluate the data. Our statisticians chose the sum of the tool wear as this criteria, and thereby selecting Carboloy 44A as a superior material and the baseline geometry speeds and feeds as the better conditions.



PRIMARY LAND WIDTH

BLEND POINTS



FINISH OF GRIND

Figure 19. Cutter Geometry Photographs from Post-Grinding Inspection.

LABORATORY CONTROLLED CUTTER EVALUATION PROGRAM - Continued

POCKET	REMOVED VOLUME OF METAL
A	5 cc
B	6 cc
C	6 cc
F1	1 cc
G	1 cc
H	1 cc
F2	1 cc

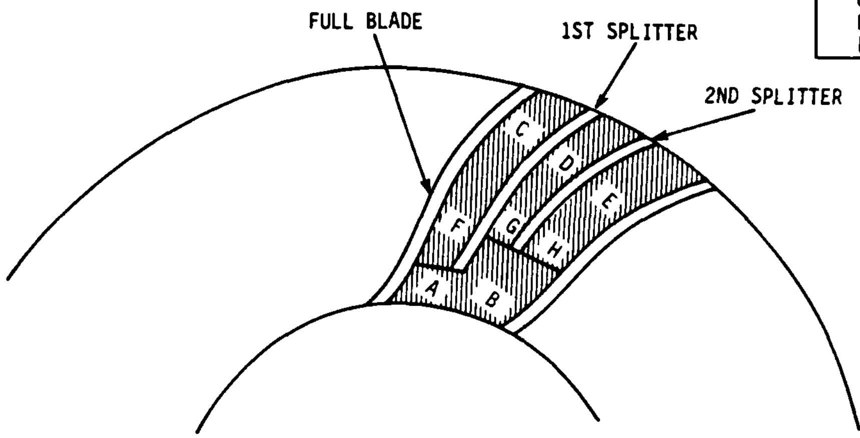


Figure 20. T700 Impeller Pocket Layout.

A more physically pertinent analysis, based on the least amount of maximum flute wear governing the wear rate, shows Ramet I and all other baseline conditions to be the best parameters. Additional testing proved that the tools with a highly worn flute soon failed a flute catastrophically and led us to prove the Ramet I material in our verification tests in Hooksett.

Data Analysis

The Laboratory Controlled Cutter Evaluation, a factorial experiment was run using a 3-3-2-2 factorial analysis of variance. The analysis of variance is a statistical procedure whereby the total measured variation is partitioned and tested by the residual error to determine the magnitude of this ratio. If a factor is insignificant, the ratio of factor to residual error approaches unity. Ratios with larger values are 'F-tested'.

The F-ratio is a statistical test to see if the partitioned segment of variance is significantly larger than the residual error component of variance. If it is, we can conclude that there is a significant effect present.

NOSE CHIPPING

WELDING

WELDING FLUTES FILLED

TYPICAL TOOL WEAR AND GEOMETRY DESCRIPTION

Figure 21. Typical Cutters After One Pocket of Metal Removal.

LABORATORY CONTROLLED CUTTER EVALUATION PROGRAM - Continued

The data analyzed by these methods indicate that the most significant effect was a first order interaction term TXG (Cutter Type + Geometry) combined effect. The second most significant effect was a main effect T (Cutter Type). These were followed by: TXMXG (Cutter Type + Cutter Material + Geometry); TXF (Cutter Type + Feed), etc.

In other words, for optimizing the process yield per cutter, we should first address the combined factors of cutter type plus geometry of that cutter.

The data indicates that Test No. 71, having combinations of T2 + M3 + G1 + F2 yielded the best results and should be the selected combination for further tests at Hooksett under actual manufacturing conditions.

Supporting preliminary data treatments that might be helpful in interpreting results attained can be found in Appendix E.

From the more physical analysis of least amount of maximum flute wear, Table 7 showed that material changes to Ramet I from Carboloy 883 could reduce wear; therefore, potentially increasing tool life. The anticipated changes in geometry did not show the expected improvements in tool life. However the material change showed an additional benefit and was pursued on a controlled basis in Hooksett during the Verification of Laboratory Results, discussed in the next section.

TABLE 7. LABORATORY CONTROLLED CUTTER EVALUATION - LEAST WEAR COMBINATIONS

	Cutter Diameter, inch		
	5/16	1/4	3/16
Chipload	Baseline	Baseline	Baseline
Material	Ramet I	Ramet I	Ramet I
Geometry	Baseline	Baseline	2-Flute

PRODUCTION VERIFICATION OF LABORATORY TESTING

Results of the Laboratory Cutter Life Evaluation testing of Phase II showed that the cutter material was the most important factor affecting cutter life. Of the three cutter materials tested in Phase II (Carboloy 883, V.R. Wesson Ramet I, and Carboloy 44A), Ramet I showed the most improvement over the baseline material, Carboloy 883. (Note: Phase I of this program evaluated several carbide grades - those chosen for Phase II evaluation showed the greatest potential for cutter life improvement.)

Scope

The intent of the Production Verification Program was to verify laboratory test data in the shop environment at Hooksett, NH. Table 8 shows a brief description of the scope of this verification.

TABLE 8. SCOPE OF PHASE II OF T700 CUTTER LIFE IMPROVEMENT PROGRAM VERIFICATION
- Order blanks for roughing cutter testing in Hooksett.
- Develop inspection technique for cutters produced on Huffman grinders.
- Develop criteria for evaluating worn cutter condition: when to change cutter.
- Run program derived cutters versus present production cutters.
- Inspect cutter after cutting.
- Inspect surface finish of parts: compare results.
- Develop cutter drawings for inspection and ordering.

Cutter Grinding Procedure

Ramet I, the cutter material recommended as a result of Lynn statistical testing, was ordered in sufficient quantities from Standard Industrial Inc., North Springfield, VT, in October 1983 in 3/16, 1/4, 5/16 inch diameters and random rod lengths. When the order was received the material was sent to Atlantic Industrial Supply Co., Warren, MI to be centerless ground to the proper diameters and cut to 4 inch lengths. After this operation, 50 blanks of Ramet I and 50 blanks of Carboloy 883 (3/16-inch diameter) were sent to Wetzell Tool Co., Bloomfield, CT for prefluting prior to grinding at Hooksett.

The cutters were ground at General Electric, Hooksett, NH on an 8-axis Huffman CNC cutter grinder built by the Huffman Corp., Clover, SC. The machine is identical to the machine used in Lynn, MA to grind the cutters used in Laboratory Controlled Cutter Evaluation. A schematic of the 8-axis machine is shown in Figure 22 (pg 43).

A representative from the Huffman Corporation was brought into Hooksett to the manufacturing engineers, operators, and maintenance people on the capabilities, usage, and maintenance of the 8-axis CNC cutter grinder. The effects of all the various Huffman parameters on the cutter geometry were reviewed.

PRODUCTION VERIFICATION OF LABORATORY TESTING - Continued

Cutter Inspection

All cutters were inspected after grinding for:

- primary land width
- blend points
- finish of grind
- end geometry
- quality

See Table 9 (pg 43) and Figures 19 and 20 (pgs 37-38).

To insure consistency and quality, cutter inspection was done at the grinding station immediately after grinding each cutter. As in the laboratory evaluation, each cutter was coded by material.

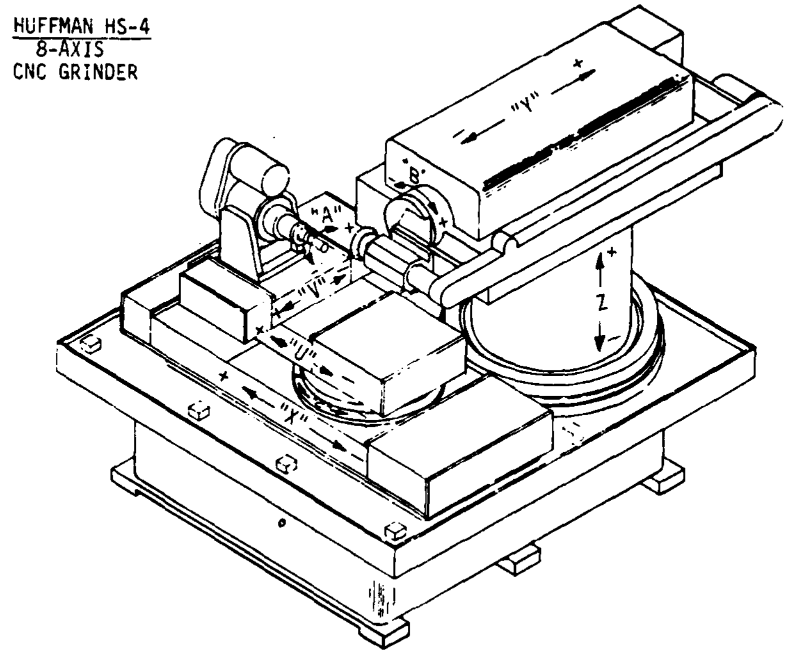


Figure 22. Huffman 8-Axis CNC Cutter Grinder.

TABLE 9 CUTTER GEOMETRY INSPECTED PRIOR TO TESTING

ITEM	PURPOSE
o Primary Land Width	To maintain consistency of primary width from flute to flute and also from nose to shank.
o Blend Points	To assure that end geometry and side cutting geometry are properly blended at the radius.
o Finish of Grind	To maintain a smooth ground surface in all areas.
o End Geometry	To assure that end mill has proper "drilling" geometry.
o Quality	To detect the presence of any chips, nicks, cracks and voids that could cause the cutter to fail.

PRODUCTION VERIFICATION OF LABORATORY TESTING - Continued

Test Procedure

The verification testing was done on a rigid 5-axis, 4-spindle milling machine, developed for blisk and impeller machining by Rigid LTD., Rorschachenberg, Switzerland and uses a GE 1050 control. A schematic of the 5-axis miller is shown in Figure 23 (pg 45). All impeller and blisk programs were downloaded from the Honeywell Computer to the GE 1050 controller. A description of blisks and impellers is presented in Appendix G.

Cutters are loaded into the double-angle collets of the toolholders, rough gaged to the correct extension, and then installed in the machine and finished gaged using gage blocks and tool offsets.

The blisk and impellers were then machined according to the NC program. Cutters were changed according to the test schedule shown in Appendix F. After each test, the cutters were inspected. Table 9 (pg 43) lists the parameters that were inspected to assess cutter wear life. Figure 24 (pg 46) depicts some of the typical characteristics.

Initial verification testing entailed running program derived cutters (Ramet I) under identical conditions with present production cutters (Carboloy 883) to a point when the cutters would normally be changed. The tool wear was then measured for the amount of wear on the primary land of each cutter and compared (Tests 1, 2, 3, 4, 5, 6-13, 14, 15, 16, 17, 18, 19, and 20)*. During this testing, Ramet I showed significantly less wear than Carboloy 883 in the milling of blisks and impellers.

In an attempt to quantify how much additional tool life could be obtained from Ramet I, a second series of tests was run. These tests consisted of running Ramet I in all 4 spindles until the tools were worn to the same condition as the Carboloy 883 tools of the previous test cutting performance (Tests 21, 22, 23, and 24-27).

A third test was also run at this time (Test 28) which used Ramet I in all spindles throughout the complete roughing cycle of an impeller to determine how much of a reduction in cutter usage would be realized.

Data for this and other testing are shown in Appendix F.

Cutter Testing Results

As a result of 6 months of controlled implementation of the laboratory results in Hooksett, significant increases in cutter life were recorded. The laboratory results of increased life with Ramet I was verified. This resulted in Hooksett procuring the new material in its annual purchase. When completely implemented, this material should reduce cutter usage by an additional 10% to approximately 80 cutters per engine set.

*Data for all tests is shown in Appendix F.

REFERENCE POSITION FOR AXES AND MOTION DIRECTION

X LONGITUDINAL LEFT HAND SIDE

Y TRANSVERSE, AT FRONT

Z VERTICAL, UPWARDS

A TILTING 10° BELOW HORIZONTAL

B CIRCULAR, OPTIONAL

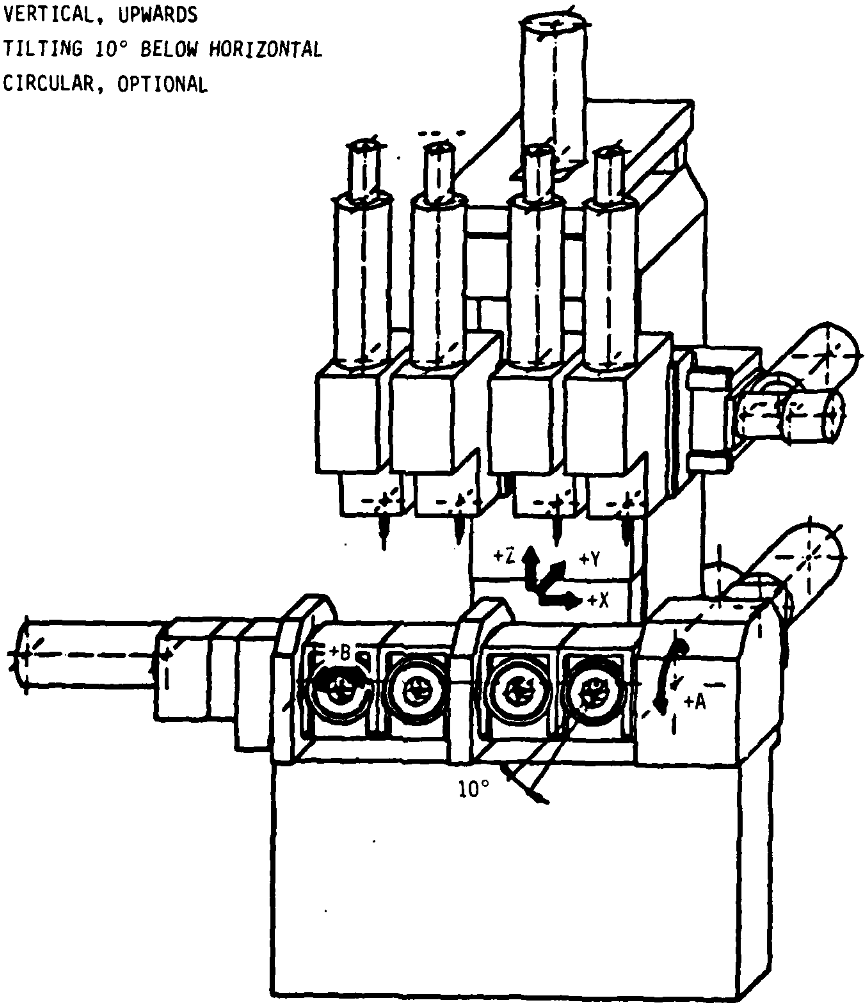


Figure 23. Rigid Miller Schematic

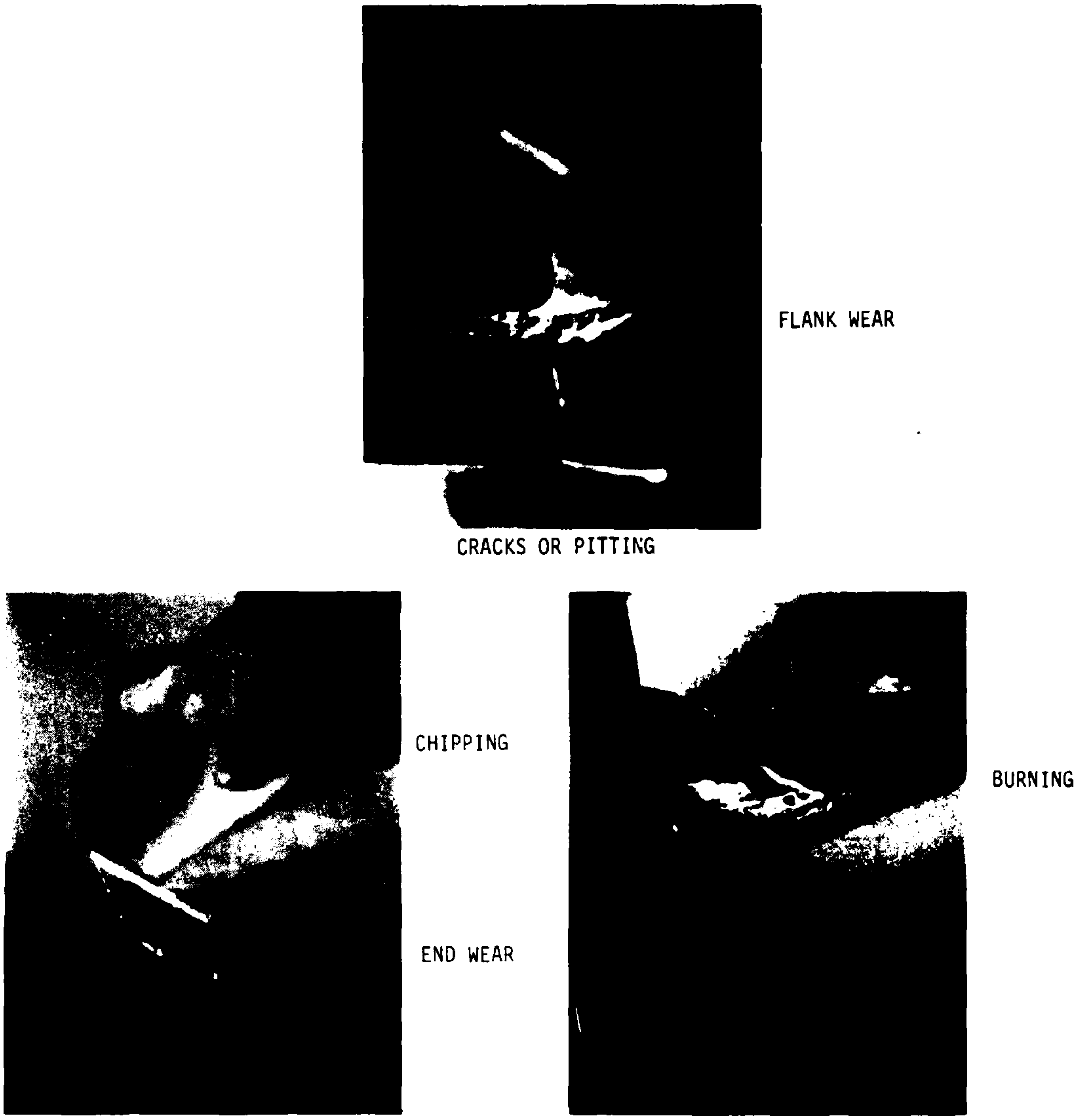


Figure 24. Wear Indications Inspected to Assess Cutter Wear.

CUTTER INSPECTION SPECIFICATION

Pre-inspection and post-inspection of cutters was accomplished using a Dynascope (Stereo Microscope) manufactured by Vision Engineering Ltd., England, and a Stocker and Yale Tool Analyzer manufactured by Stocker and Yale, Beverly, Mass.

The Stereo Microscope (see Figure 25, pg 48) projects the image of the cutter on a screen which is viewed with both eyes making it a very comfortable system with practically no eye strain. The maximum magnification of this unit is 50X with improved capabilities of resolution lending itself very well to the needs of tool grinding inspection.

The Stereo Microscope model used is not set up for inspection of end geometry so the Stocker and Yale Tool Analyser (see Figure 26, pg 49) used previously was retained. In this system, the cutter is held horizontally in a collet with the operator looking through a single horizontal eyepiece, which rotates on a horizontal plane so that the cutter can be viewed from the side as well as from the end.

Prior to this program, the inspection equipment was limited to magnification's not greater than 10X.

Equipment used was:

1. 5X magnification glass 6-inches in diameter using a "Halo" neon illuminating tube.
2. Closed circuit T.V. system with 10X capabilities.
3. Stocker and Yale Tool Analyser with 10X capabilities.

CUTTER INSPECTION INVESTIGATION

As the complexity of the geometry of the cutter increased, so did the need also increase to view, scrutinize, and measure the geometry to make changes thereon and to check the quality of the geometry and material.

Inconsistancy in cutters purchased from various vendors led to in-house grinding of cutters on the Huffman 8-axis cutter grinder. However inspection of the cutters to insure a quality and repeatable product was difficult. A survey of available inspection systems capable of inspecting the complex geometries of cutters was undertaken.

The results of this survey revealed that no one system was available to inspect the necessary geometries parameters. Therefore, a functional specification GE Specification No. 0283-I was developed (Appendix H). The specification covers a system that will allow for precision positioning and measuring of cutter geometry requirements and be capable of identification of all undersireable features in the required cutting zone and where cutter runout and size are to be considered in as a part of cutter geometry. A final Specification was developed based upon input to the functional specification. The final specification is shown in Appendix H.

The following is a review of various vision methods for usage in a cutter inspection station.

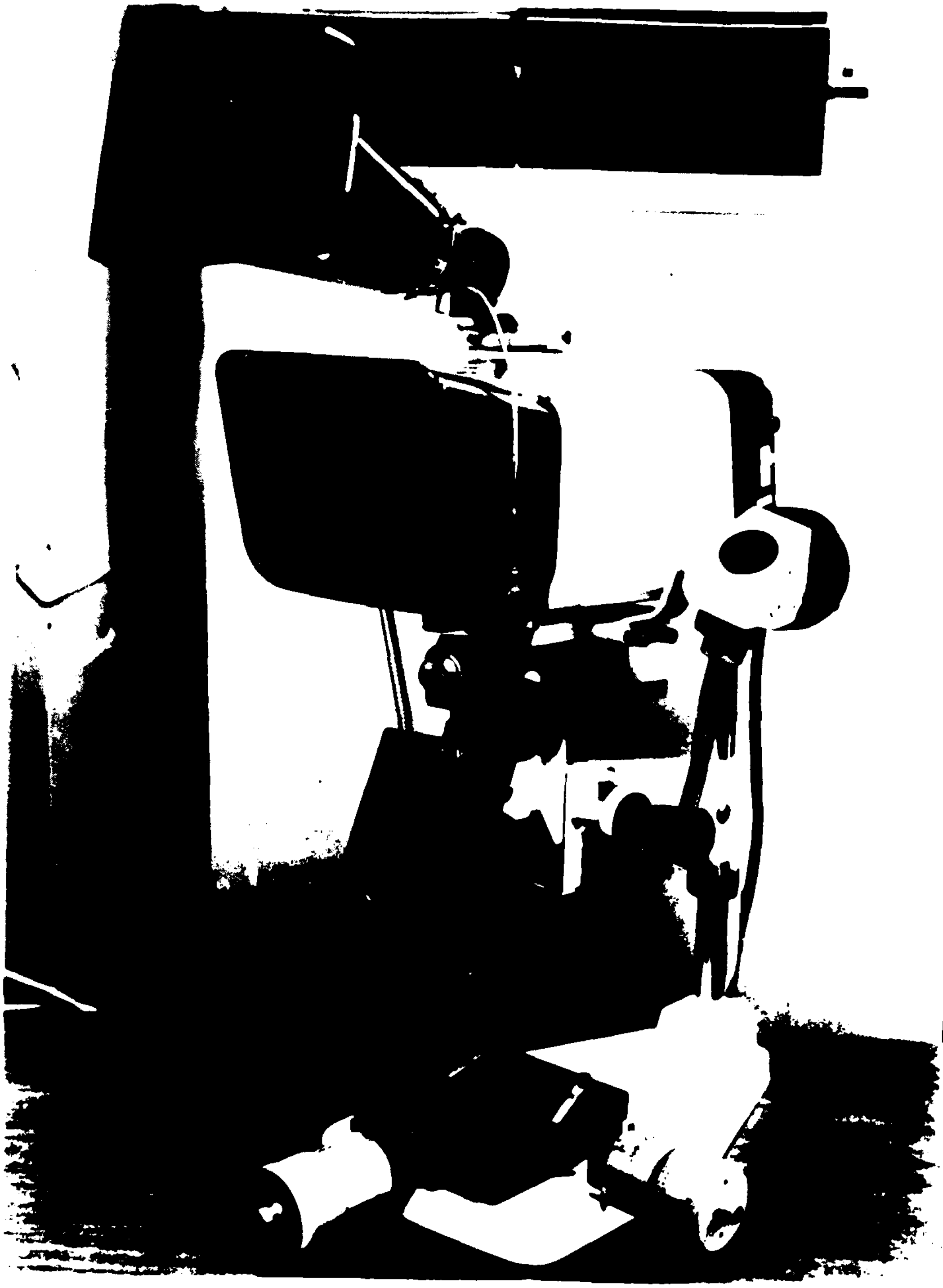


Figure 25. Dynascope Used for Cutter Inspection.

4-AXIS TOOL ANALYZER

Figure 26. Stocker and Yale 4-Axis Cutter Analyzer.

VIEWING METHODS

TV - Black and white TV is not adequate for the purposes of viewing the completion of milling cutters. Only color show the contrasts necessary for operator viewing, of the cutter, however only a color monitor of the highest quality is adequate. Lighting for each size and style of cutter could not be constant, fixed source for TV, as lighting is extremely critical for TV. This may cause operating problems if incorporated into a multipurpose inspection machine. When using TV, the area of the cutter which can be viewed is limited.

This then required an extreme number of locations for the operator to move the cutter to, making viewing discontinous. Considering the complexities of the cutter geometry, the difficulties in lighting the tool, and the area which can be viewed, etc., T.V. can not be recommended for either an operator used manual, or semi-manual, piece of equipment.

COMPARATORS

For the projection of the cutter, a comparator system is excellent. However, in using projection, such details as land width, the quality of grind, or position of each flute relative to another, etc. cannot be viewed or measured. This problem however can be eliminated through the use of surface illumination, but it must be of the highest quality. The present surface illumination standard in the industry, is not deemed adequate for viewing the cutters at the magnifications required. The area of surface illumination may require further development.

Another objectionable feature of the comparator is the limited depth of field. The constant refocusing of the comparator as one views the cutter at different positions when using surface illumination can be a tedius and frustrating operation. For proper evaluation of a cutter one needs zooming capability when under surface illumination measurement. The present comparators do not have this feature. To increase magnification on standard comparators requires the changing of lenses in the optical path. Again, this required refocusing of the comparator. The use of a comparator, as equipped today, would be extremely labor intensive and time consuming.

Microscopes

Microscopes in general are not designed for the industrial environment. The use of microscopes requires specialized handling and care, care which cannot be guaranteed in an industrial environment. Calibration of microscopes are easily changes when the optics are used for measurement. Viewing through a microscope is fatiguing to an operator and his vision. The "Vision" Dynascopic had some good features about it that overcame some problems listed above. This plano-scope was good for certain types of measurement but depth of field again was critical.

The Stero-Dynascopic offered the greatest potential but one measurement was not possible thorugh the optics, and parallex error was substantial. Such a system may be fine for analytical work with a technician for qualitative and some quantitative analysis, however it is not recommended for production inspection of cutters.

CUTTER INSPECTION INVESTIGATION - Continued

Standard Cutter Inspection Tools on the Market Evaluated

Evaluation of equipment manufactured by Stocker and Yale, Strasfan and Titan was done. None of these tools priced from $6,000 to $19,000 could be considered adequate to measure cutter geometry required for precision control of cutters for the T700 blisk manufacturing program.

Clearly, no one vision system is adequate to define all critical areas of a milling cutter. Of those investigated, only the microscope with screen projection was deemed suitable for usage. However, its survival in a industrial environment is questionable.

For the tool holding, positioning,and data accumulation, off the shelf technology exists and is well within reasonable costs for a cutter inspection machine. Automatic data collection, because of the high numbers of features to be inspected on a cutter is recommended.

In addition, an integrated CRT display would be desirable to lead an operator through a predetermined measuring sequence. With auto positioning of a cutter, and edge finding capability for projection images now becoming available in modern day comparators, much of the data necessary for milling cutter inspection could be automatically be taken, and stored.

Using surface illumination with automatic sequencing of light it would be possible to obtain other qualitative and quantitative data required with minimal operator interaction.

One other method has yet to be evaluated. Pictures of a cutter, could be digitally compared to that of a master cutter. With masters and duplicate lighting and analysis done by a computer, no operator would need to be involved. Data could be stored for each cutter and if failure occured, the photograph could be evaluated.

To build such a piece of equipment will require development funding. The technology is available, but has not been directed towards manufacturing. While no firm proposal came out of this investigation, it has shown that no suitable equipment is available in the U.S. market and that none of the vendors who would supply the consumer has the full knowledge required to adequately measure this type of tooling. There is a need for it, but funding will be required to build a system. Equipment which is available is slow and requires a person very familiar with cutters, and their measurement along wth other decision-making aspects, to determine cutter quality. A new piece of equipment based upon comparator principles is required.

CUTTER INSPECTION INVESTIGATION - Continued

Results

A simplified cutter inspection station was developed and installed in the cutter grinding area. Machine operators and cutter grinding operatoars have access to this equipment to insure the quality of cutters they produce and use in production.

After receiving comments and quotes from inspection equipment manufacturers based on a functional specification developed at GE, a final specification (Appendix H) was prepared incorporating the manufacturers comments and suggestions to develop a system more dedicated to the inspection of these complex cutters.

IAG IMPROVED CUTTER DRAWINGS

The drawings of the cutters were developed by the Inter-Active Graphics Department of Building 40, G.E. Lynn. Mass. These drawings were computerized for flexability and give an excellent detail of cutter geometry, and are compatible with Huffman cutter grinding parameters. The drawings are shown in Appendix I.

Computerized IAG was also used to produce 3-dimensional images of an impeller roughing cutter (Figure I-2) to determine the feasibility of using this graphics system as a cutter design aid. It was determined that the only way this system could be used effectively as a cutter design aid would be by post-processing the Huffman tape information and using it to control the graphics system. This could not be achieved within the scope of this program.

PHASE II SUMMARY

At the start of this program, a total of 134 cutters were used to produce the T700 compressor section rotating components for each engine. Current cutter usage is a total of 88 cutters per engine. This reduction represents a savings of 28% of the cutters on Stage 1, 46% on Stage 2, 7% on Stages 3 and 4, 22% on Stage 5, and a 41% reduction for milling the impeller.

As a result of Phase I, areas showing the need for further investigation, such as increasing cutter life by understanding and optimizing the effects of speed, feed, geometry, and material; the effect of various coolants; and the benefits of tighter inspection of incoming cutters, were investigated in Phase II.

In order to utilize the capabilities of the 8-axis CNC cutter grinder to the fullest extent, a representative of Huffman Corporation worked with the Manufacturing engineers and machine operators at Hooksett to show them the machine capabilities and the effect of the various Huffman 8-axis CNC cutter grinder parameters on the cutter geometry.

PHASE II SUMMARY - Continued

Use of the milling computer simulation developed by Professor Nathan Cook of MIT revealed some inadequacies, such as inadequate chip clearance, in our baseline cutter geometries. Micrograin carbides, due to their ability to be ground to a sharper edge (due to its small grain size), also showed potential improvements.

A statistically designed 3-3-2-2 factorial experiment was developed and run to determine the independent and coupled importance of speed, feed, cutter material and cutter geometry on cutter life.

The materials recommended in Phase I, with an additional micrograin recommended from the computer simulation were evaluated in the Laboratory Controlled Cutter Evaluation.

Cutter material grades and geometries deemed as having high potential for increasing cutter life from the statistical laboratory tests were brought into the production environment for controlled testing and implementation. Implementation of the lab results in this six-month program showed an additional cutter usage savings of 10%. As a result, the material and geometry changes have been accepted and are being implemented throughout the shop.

A seven-month study of cutting fluids on production equipment showed little difference in cutter usage. A change of cutting fluid was, therefore, not implemented due to the high changeover costs.

Interactive Graphics (IAG) was utilized to unify cutter drawings and specify the detail necessary to describe the complex geometries required for milling T700 blisks and impellers.

A detailed investigation of commercially available cutter inspection equipment was completed. As a result of adequate equipment being unavailable, a functional specification was developed for an inspection station.

A cutter inspection station was developed and installed in the cutter grinding area. Machine operators and cutter grinding operators have access to this equipment to insure the quality of cutters they produce and use in production. A specification for a more automated inspection station has been developed for use in procuring a system more in tune with the factory automation plan.

PHASE II RECOMMENDATIONS

After completing several months of verification testing at Hooksett, NH; the following recommendations for implementation are made as a result of the Phase II verification testing, and are areas to be considered for further development.

- Cutter runout should be checked with an indicator prior to the cutter grind operation. During verification we discovered that even minute eccentricities will lead to a cutter with inconsistant flute geometries; These inconsistent flute geometries, i.e., the primary land, will severely reduce cutter life.

- Cutters should be checked 100% visually for cracks, nicks, pits and voids, finish of grind, uniformity of primary land width, cutter diameter, and blend points at radii, after grinding and before cutting using the Vision System Stereo Microscope (Dynascope). The Vision System microscope has enabled previously undetected life limiting deficiencies to be detected prior to using the cutter. Detecting these flaws will reduce scrap caused by fractured cutters.

- Ramet I appears to be a clear-cut choice over Carboloy 883. Hooksett has proceeded to procure Ramet I for use in the production of impellers and blisks.

- Further investigation should be done on the geometry of the 1/4 inch and 3/16 inch roughing cutters. This should include:

  - Chip exit area (where bottom gash meets the gullet area between the flutes). Some cutters are still showing evidence of excessive rubbing in this area.

  - Reducing the helix angle to improve the strength. Under present cutting loads, cutter strength is adequate. However, improved cutter strength, coupled with implementation of adaptive control may allow heavier cuts.

  - Testing three fluted tools. Increased chip exit area and improved cutter rigidity may show further cutter improvement.

PROGRAM SAVINGS

PROGRAM SAVINGS

As a result of this program, reduction in the cutter usage from 134 cutters per engine set (at the start of the program) to 88 cutters per engine set has already been experienced. It is projected that implementation of the new cutter material will result in further reduction to 80 cutters per engine set. Reduction in the usage of each cutter type and for each component is shown in Figure 27 and Figure 28 (pg 56) respectively.

Reduction in the cutter usage to 88 cutters per engine set will result in projected direct labor and indirect manufacturing expense (overhead) savings of $7.8 million (then year dollars) for all military production over ten years. Projected savings corresponding to 88 cutters per engine set will be $9.3 million.

As the Hooksett Plant and Rutland Plants have a common overhead pool, savings in indirect manufacturing expense will affect all products manufactured in these plants on an equal basis. As a result, the Army share of the savings on T700 engine programs will be $1.8 million, corresponding to a reduction in cutter usage to 88 cutters per engine set and $2.2 million corresponding to a reduction in cutter usage to 80 cutters per engine set.

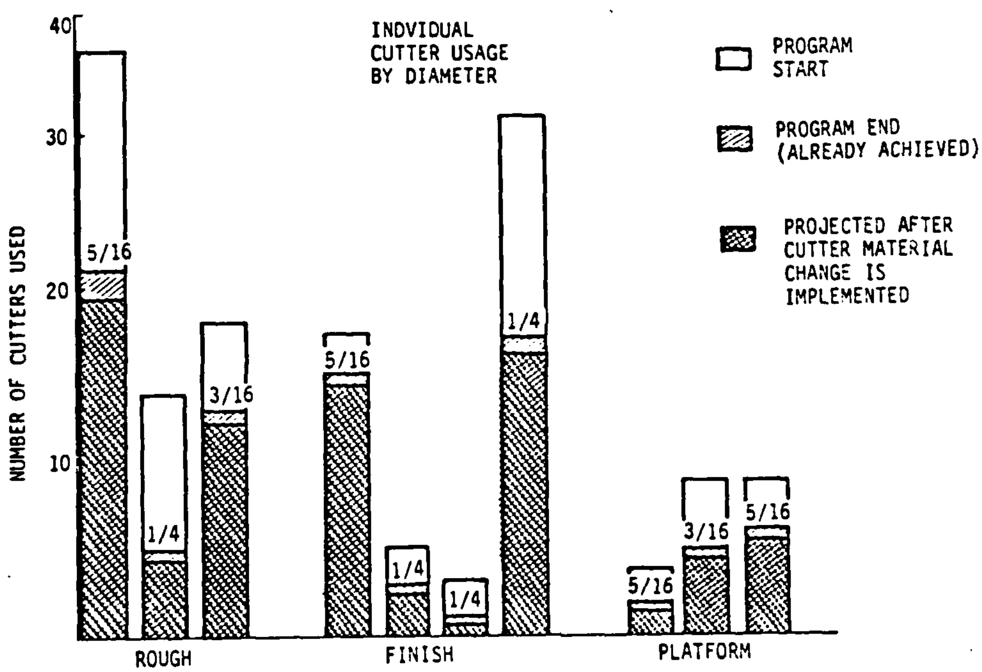


Figure 27. Change in Number of Cutters Used for Machining T700 Blisks and Impellers.

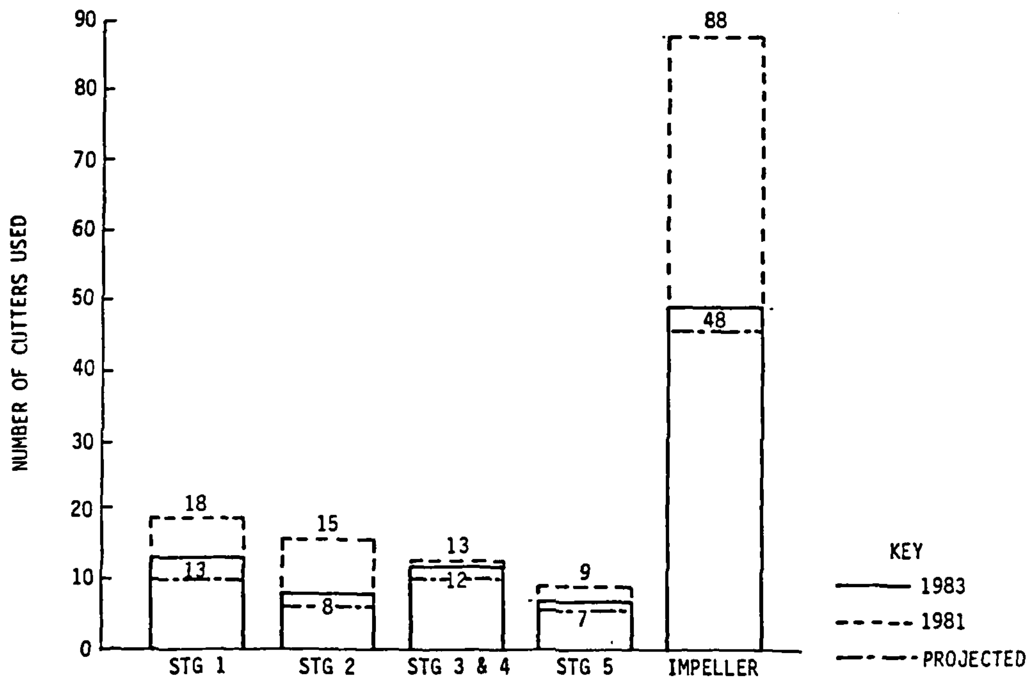


Figure 28. Cutter Usage by Component.

CONCLUSIONS

AND

RECOMMENDATIONS

CONCLUSIONS

The Army T700 Cutter Life Improvement Program funded under Contract No. DAAK50-81-C-0029 was completed December 1983 and has already resulted in a 34% reduction in the cutter usage. Reduction in the cutter usage will increase to 40% after the change in the cutter material is implemented. This equates to a total projected Military savings of $9.3 million ($7.8 million already experienced). Army share of the savings is $1.8 million (already experienced) and $2.2 million with the additional implementation of new cutting materials.

As a result of this program, methods to isolate and reprogram NC programming deficiencies in 5-axis milling were developed. Improved cutter quality on the shop floor, due to keen awarness of the complexity of cutter geometries and newly installed inspection equipment, has been realized and provided over a 20% reduction in cutter usage.

More consistent airfoils, due to more rigid toolholders implemented during this program, have also been realized. This contributes to a more efficient and higher performance T700 engine and an improvement in the life of all cutters used.

Ramet I was tested in the production environment and, as in laboratory testing, exhibited superior cutter tool life compared to Carboloy 883, and has been selected for production use.

Additional efforts for production verification, including improved IAG cutter drawings, a GE specification for cutter inspection, and a listing of the inspection equipment used to inspect the cutters described in this report are shown in Appendixes G, H, and I.

RECOMMENDATIONS

This program explored several methods to increase cutter life for the T700 compressor section. As beneficial modifications to existing processes became apparent, the processes were modified to reduce milling costs and to maximize savings. As new material, geometries and inspection techniques were implemented, cutter life increased further.

Hooksett will continue to implement the Ramet I material as new baseline material for all cutters. An initial 1-year supply has been ordered and will be phased into production. As new materials become available, these should be tested in an effort to find even better materials.

Inspection of each cutter, prior to usage is a must. This will insure each machine will be utilizing the best tooling available.

Grinding of the cutters is critical. Each carbide blank will be mounted in the grinding tube and indicated to minimize eccentricity. This will insure consistent flute quality in the Huffman grinding operation.

Studies on cutter geometry are being continued. By evaluating worn tools, more geometry changes to increase life may become apparent. Several changes have become obvious during this study. These have been implemented.

Automation of the cutter grinding operation should be pursued. With the increase in cutter grinding capabilities in Hooksett (increased from one to four Huffman grinders) this can have some significant benefits. Automating inspection via vision system and computerized data acquisition system should be investigated to reduce operator input.

And finally, purchase of a coercive force measuring machine to inspect incoming carbide blanks is required. Disruption of production due to poor material quality could be minimized with proper inspection of incoming material.

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REFERENCE LIST

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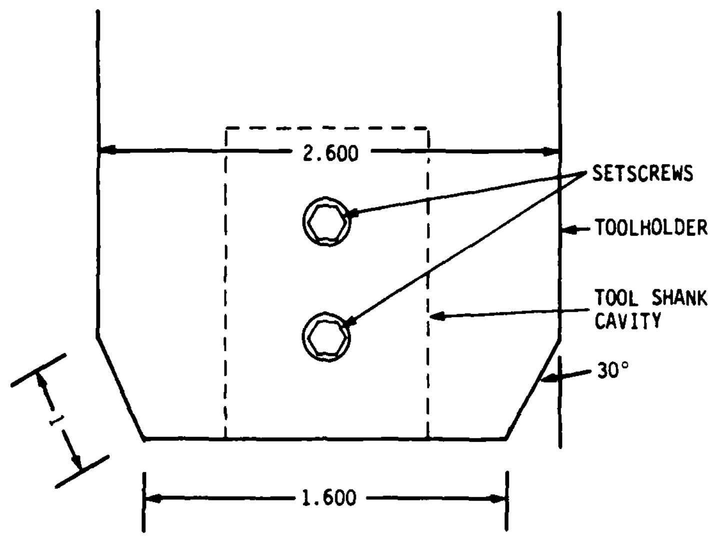
BLANK

APPENDIXES

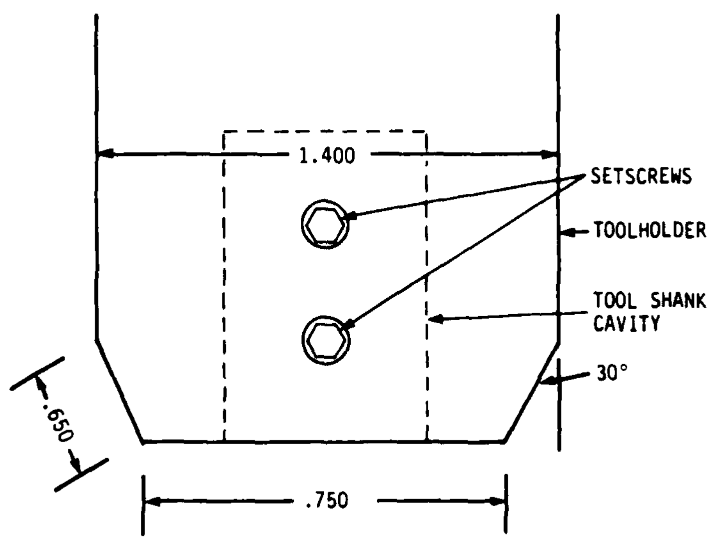
APPENDIX A

OPTIMUM TOOLHOLDERS DESIGN

Optimum designs for toolholders used on each pocket of the impeller are shown in this Appendix. Blisk toolholders were considered optimized since toolholder clearance above the airfoil was already minimized thereby allowing a very rigid structure. The following designs were not implemented due to difficulties in toolholder control and risks of using the incorrect toolholder.

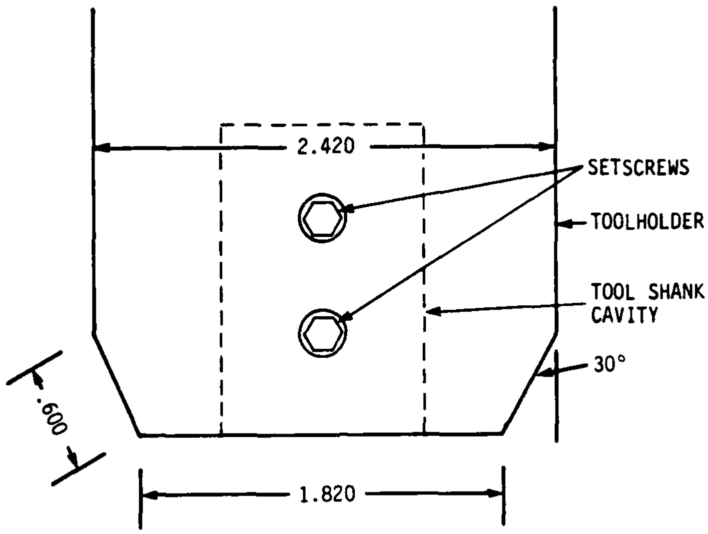


IMPELLER POCKET A TOOLHOLDER

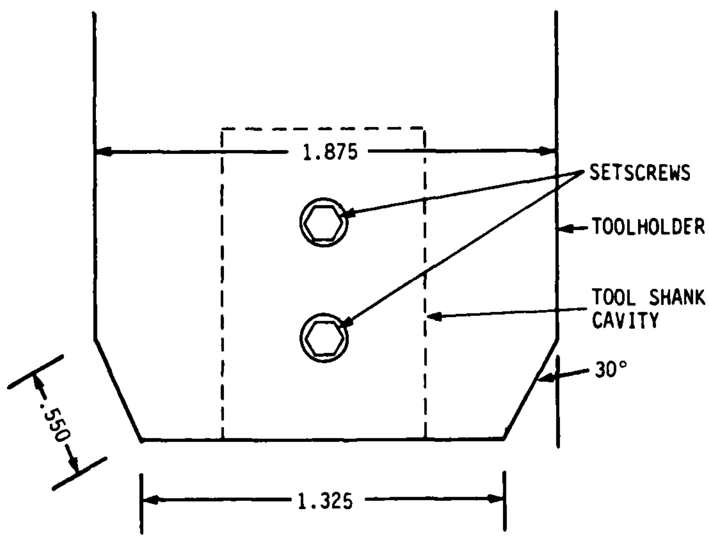


IMPELLER POCKET B TOOLHOLDER

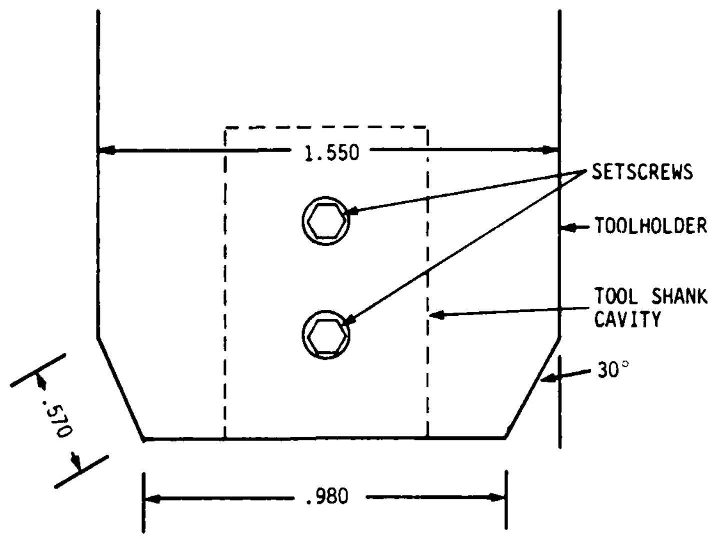
APPENDIX A



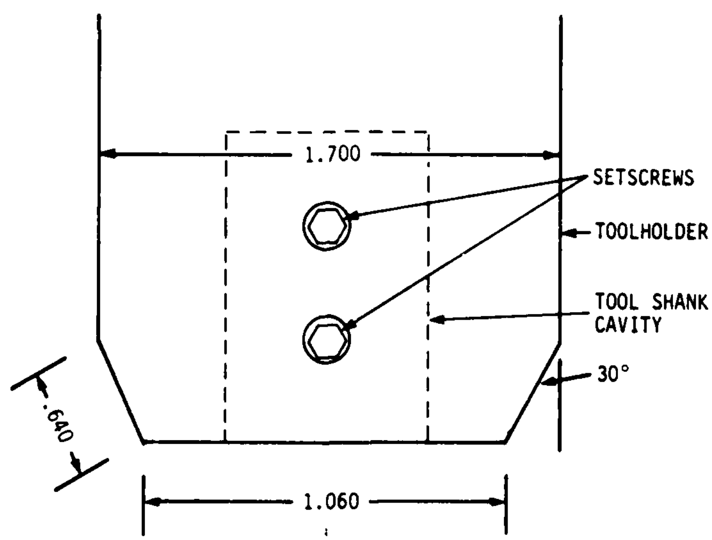
IMPELLER POCKET C TOOLHOLDER



IMPELLER POCKET F TOOLHOLDER

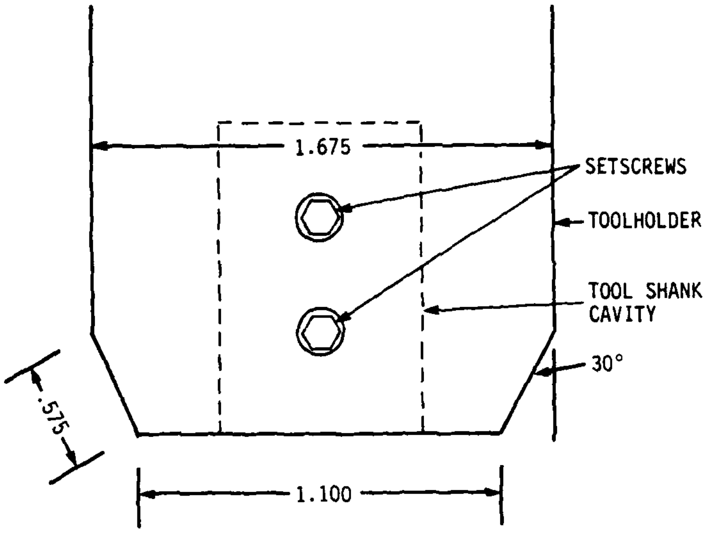


IMPELLER POCKET F2 TOOLHOLDER



IMPELLER POCKET G TOOLHOLDER

APPENDIX A



IMPELLER POCKET H TOOLHOLDER

BLANK

APPENDIX B

MILLING SIMULATION PROGRAM

This Appendix contains the BASIC code used in the computer simulation of the milling process. It is reprinted with the permission of its author Professor Nathan Cook, Professor of Mechanical Engineering, MIT. This program was run on a North Star computer.

Current - 5/4/82

APPENDIX B

```
10  REM       SIMULATION OF MILLING PROCESS   vers. 3.0   4/14/82
20  REM            (C)  N. H. Cook  1982
30  REM                filed under "MILL"
40  REM
50  REM            ***  TOOL DATA  ***
60  REM
70  LINE 132
80  N1=6           \REM  Number of teeth
90  R1=.5*5/16     \REM  Mill radius (in)
100  L1=2           \REM  Tool overhang (in)
110 A1=0           \REM  Rake angle (degrees)
120 G1=6           \REM  Relief angle (degrees)
130 REM            \REM  Corner angle info.
140 R3=00          \REM  Initial wear (radial, in)
150 E1=94*10^6     \REM  Tool Modulus (psi)
160 S1=290000      \REM  Trans. Rupture Stress (psi)
170 K9=13          \REM  Thermal conductivity (lb/sec/F)
180 C9=210         \REM  Volumetric specific heat (lb/in^2/F)
190 W9=.005        \REM  Failure wear land (in)
200 Q9=40000       \REM  Thermal activation energy for wear-land wear (cal/mole)
210 D9=5000        \REM  Diffusion wear constant (in/sec)
220 D9=50000       \REM  Accelerate wear process
230 K8=K9/C9       \REM  Thermal diffusivity (in^2/sec)
240 T9=SIN(G1/57.3)/COS(G1/57.3)     \REM  Tangent of gamma
250 F9=.67*.79*S1*(R1^3)/L1          \REM  Fracture load, Kt=1.5 (lb)
260 REM
270 REM            ***  WORKPIECE DATA  AM355  ***
280 REM
290 H=350          \REM  Brinell Hardness (325-388)
300 U9=500000      \REM  Specific Energy at t=.01 in.
310 B=45           \REM  Effective "friction angle" beta
320 A5=(B-A1)/57.3\REM  Beta-alpha (rad)
330 REM
340 REM            ***  PROCESS DATA  ***
350 REM
360 N=2760         \REM  Spindle RPM
370 F=4.2          \REM  Feed Rate  in/min
380 W=.3125        \REM  Width of cut (radial depth)
390 D=.06          \REM  Axial depth  of cut (alter in program)
400 T$="UP"        \REM  UP or DOWN milling
410 K0=25000       \REM  Spindle stiffness (lb/in) (from test)
420 E=0000         \REM  Spindle/tool eccentricity at tooth #1 (in)
430 E=.001
440 R2=00          \REM  Mean radial tooth error (in)
445  E9=.000005                     \REM  Max. error in defl.
450 N2=24          \REM  Increments/rev, must be integer * N1
460 A4=6.2832/N2   \REM  Delta-theta (rad)
470 V9=.1047*R1*N  \REM  Cutting speed (in/sec)
480 REM
490 L6=SQRT(R1^2-(R1-W)^2)
500 IF W>R1 THEN N6=.5*N2*(1-ATN(L6/(W-R1))/3.1416)  \REM  #incr./width
510 IF W<=R1 THEN N6=.5*N2*ATN(L6/(R1-W))/3.14166
520 REM
530 DIM X(N2/2), Y(N2/2)             \REM  x and y surface locations
540 DIM X1(N2/2),Y1(N2/2)            \REM  Dummy x-y locations
550 DIM R2(N1), R3(N1), W(N1), T(N1) \REM  Radial error,wear, wear-land, temp.
560 DIM S(N2), C(N2)                 \REM  Sine-cos table
570 T2=60/(N*N2)                     \REM  Delta-t  (sec)
580 Y2=F/(N*N2)                      \REM  Delta-y per delta-t
590 K1=3*3.1416*E1*R1^4/(4*L1^3)     \REM  Tool stiffness
600 K2=1/(1/K0+1/K1)                 \REM  Total stiffness
610 K2=1000000
```

APPENDIX B

```
620 REM        ************** INITIALIZE **************
630  I9=0                             \REM  Counter for skipping print
640 Z9=RND(-1)
650 FOR J=1 TO N1
660  R2(J)=R2*(2*RND(0)-1)           \REM  Random tooth error
670  R3(J)=R3                         \REM  Initial wear
680  W(J)=R3/T9
690 NEXT
700 FOR K=1 TO N2/2
710  A8=(K-.5)*A4
720  S(K)=SIN(A8) \ C(K)=COS(A8)     \REM  Sine & cosine table
730 NEXT
740 INPUT"Test data: ",Z$
750 GOSUB 1470                         \REM  Print Heading
760 REM
770 R=R1+E-R3
780 FOR K=0 TO N2/2 \ X(K)=R*C(K) \ X1(K)=X(K) \ Y(K)=R*S(K) \ Y1(K)=Y(K)\NEXT
790 Z=U9*D/K2                         \REM  Iteration constant
800 IF Z<1 THEN Z=1  \ Z1=Z
810 REM
820 REM       *************** RUN PROGRAM **************
830 REM
840 FOR N0=0 TO 60                    \REM  Revolutions
850  M1=0                             \REM  Sum the moments
860 FOR I=1 TO N2                     \REM  Time increment no.
870  Z=Z1
880  N9=I+N2*N0                       \REM  Count increments
890  N8=0                             \REM  Set N8=0 for next increment
900  F1=0 \ F2=0 \ M0=0              \REM  Set Fx,F,M0=0 for next tooth
910  N8=N8+1                          \REM  Count iterations
920  IF N8<=Z THEN 940
930  Z=2*Z \ GOTO 890
940  U=U+(U0-U)/Z \ V=V+(V0-V)/Z     \REM  New displ. for iteration
950   T3=0                            \REM  Sum the chip thicknesses
960  FOR J=1 TO N1                    \REM  For each tooth
970   K=I-(J-1)*N2/N1                 \REM  Angular position (N2/N1=integer)
980   IF K<=-N2/2 THEN K=K+N2
990   IF K> 0 THEN IF K<=N6 THEN IF T$="UP" THEN 1020
1000   IF K> (N2/2-N6) THEN IF K<=N2/2 THEN IF T$="DOWN" THEN 1020
1010   T=0 \ T(J)=0 \ GOTO 1220        \REM No cut, no force, no temp
1020   X0=U+E*C(I)+(R1+R2(J)-R3(J))*C(K)          \REM  x-coordinate
1030   Y0=V+E*S(I)+(R1+R2(J)-R3(J))*S(K)+N9*Y2    \REM  y-coordinate
1040   T=(Y0-Y(K))*S(K)+(X0-X(K))*C(K)            \REM  Chip thickness
1050   IF T>0 THEN 1070
1060   T=0 \ T(J)=0 \ GOTO 1220        \REM No cut, no force, no temp
1070   U8=U9*(T/.01)^-.2              \REM  Size effect
1090   T3=T3+T
1095 IF K<7 THEN D=.12 ELSE D=.06      Oval depth
1100    F3=U8*D*T                      \REM  Tangential force
1110   F4=U9*D*W(J)/6.28              \REM  Wear land tang. force
1120   IF T>R3 THEN 1140
1130   F4=F4*T/R3
1140   X1(K)=X0 \ Y1(K)=Y0                       \REM  Store shape
1150   M0=M0+R1*(F3+F4)                              \REM  Mo on spindle
1160   F1=F1+F3*SIN(K*A4-A5)/COS(A5) +F4*(S(K)-C(K))   \REM  Fx on tool
1170   F2=F2-F3*COS(K*A4-A5)/COS(A5) -F4*(S(K)+C(K))   \REM  Fy on tool
1180   REM
1190   T(J)=.4*(U8/C9)*(V9*T/K8)^.333     \REM  Tool temp. rise (F)
1200   T(J)=T(J)+(U9/6.28)*(V9*W(J)/(K9*C9))^.5   \REM  Plus land temp
1210   IF T(J)>3500 THEN T(J)=3500     \REM  Melting!
1220  NEXT
1230  U0=F1/K2 \ V0=F2/K2             \REM  Calc. elast. deflect.
```

```
1250 IF ABS(U-U0)>E9 THEN 900        \REM  Iterate if not close enough
1260 IF ABS(V-V0)>E9 THEN 900
1270 IF F9>(F1^2+F2^2)^.5 THEN 1290  \REM  Check for fracture
1280 ! \ !"Tool has FRACTURED" \ ! \ STOP
1290 M1=M1+M0 \ T1=T1+T3
1300 REM
1310 REM              *** Cut OK, now update surface profile ***
1320 REM
1330 IF I<I9 THEN 1360
1340 !%3I,N0+1,I,%6F1,F1,F2,M0,%10F5,U,V,W(1),%6F0,T(1),%6F4,T1,
1350 IF I=24 THEN !%6F2,M1/24 ELSE !""
1360 REM
1370  FOR K=0 TO N2/2 \ X(K)=X1(K) \ Y(K)=Y1(K) \ NEXT
1380 FOR J=1 TO N1
1390   IF T(J)=0 THEN 1440
1400   R3(J)=R3(J)+T2*D9*EXP(-Q9/(1.1*(T(J)+520)))      \REM  Radial wear (in)
1410   W(J)=R3(J)/T9                                     \REM  Wear land
1420   IF W(J)<W9 THEN 1440
1430   ! \ !"Tool is WORN OUT   Cutting time = ",N9*T2," sec."\!\STOP
1440 NEXT
1450 NEXT
1460 NEXT
1470 REM        **************** HEADING ***************
1480 REM
1490 !
1500 !"MILLING SIMULATION       N. H. Cook  vers. 3.0  4/14/82"
1510 !\!"       Operation: ",T$
1520 !"Mill:  Dia =       ",2*R1,        TAB(40),"E             = ",E1
1530 !"       Overhang = ",L1,           TAB(40),"Sigma-f       = ",S1
1540 !"       Teeth =    ",N1,           TAB(40),"Therm. cond. = ",K9
1550 !"       Rake =     ",A1,           TAB(40),"Vol.sp.heat  = ",C9
1560 !"       Relief =   ",G1,           TAB(40),"Q-wear        = ",Q9
1570 !"       Max.land = ",W9,           TAB(40),"Diff. wear C = ",D9
1580 !
1590 !"       Speed =    ",N," rpm",    TAB(40),"Spec. energy = ",U9
1600 !"       Feed =     ",F," in/min",TAB(40),"Frict. angle = ",B
1610 !"       Width =    ",W," in",     TAB(40),"Speed (in/s) = ",V9
1620 !"       Depth =    ",D," in",     TAB(40),"Incr in cut  = ",N6," of ",N2/2
1630 !
1640 !"Total stiffness = ",K2," lb/in           Iter. error = ",E9
1650 !"Eccentricity = ",E," at tooth #1"
1660 !"Mean radial tooth error = ",R2," in     Init. rad. wear = ",R3
1670 !"Number of steps per revolution = ",N2
1680 !"Delta-y = ",Y2," (in),  delta-t = ",T2," (sec)"\!\!
1690 !" NO  I    Fx    Fy    Mo        U         V        W(1)  T(1)  Tsum  Mbar"
1700 !
1710 RETURN
```

APPENDIX C

CUTTING FLUID EVALUATION DATA

The following data represents the average tool usage for each compressor stage and coolant. Three coolants, typical of industrial recommendations, were evaluated.

	Stage 1		Stage 2		Stage 3	
Coolant	916	910	916	910	916	910
	Avg. Tool Usage		Avg. Tool Usage		Avg. Tool Usage	
Rough	5	11	5	3	2	2
Finish	3	2	3	3	2	2
Platform	2	2	1	2	1	1

	Stage 4		Stage 5		
Coolant	916	910	916	910	958
	Avg. Tool Usage		Avg. Tool Usage		
Rough	2	2	2	2	2
Finish	2	3	2	2	2
Platform	1	1	1	1	1

APPENDIX C

CUTTING FLUID EVALUATION DATA

	Stage	Impeller	
	Coolant	916	958
		Avg. Total Usage	
	Rough		
POCKETS	A	1	1
	B	2	3
	CDE	4	5
	G	3	3
	H	3	3
	F1	4	5
	F2	6	3

Stage	Impeller Average Tool Usage (No. of Cutters)	
Coolant	916	958
Finish		
Profile L.E.	1	1
Rad. L.E. F.B.	0	0
Rad. L.E. 2nd Sp.	0	0
Rad. L.E. 1st Sp.	1	1
Hub Cont	9	7
Fin. Full Blade	5	12
Fin. 1st Splitter	6	12
Fin. 2nd Splitter	4	6
Rad. Fillet F.B.	1	1
Rad. 1st Splitter	2	1
Rad. 2nd Splitter	1	2

APPENDIX D

CUTTER WEAR DATA FROM THE LABORATORY CUTTER WEAR EVALUATION PROGRAM

The following data represents the wearland on each of the cutters evaluated in the laboratory. The coding is as follows:

A, B, C, D, E, F, G_1-G_6

A - Number of Pockets Cut:

- 0 Inspection prior to cutting
- 1 After 1st pocket of cutting
- 2 After 2nd pocket of cutting

B - Cutter Diameter:

- 1 5/16 inch
- 2 1/4 inch
- 3 3/16 inch

C - Material:

- 1 Carboloy 883
- 2 Ramet I
- 3 Carboloy 44A

D - Geometry:

- 1 Baseline
- 2 Increased primary land clearance

E - Feed Rate:

- 1 Baseline
- 2 2X Baseline

F - Test ID number.

G_1-G_6 Primary land width measurement (inches).
(Note 1E11 represents no flute, i.e., 4 flutes rather than 6)

```
900  /REM DATA IS ENTERED IN THE FOLLOWING FORMAT:
910  /REM      NO. OF POCKETS CUT; 0,PRE-INSPECTION;1,OR 2
920  /REM      TOOL NUMBER;  1=5/16"; 2=1/4"; 3=3/16"
930  /REM      MATERIAL;  1=883; 2=RAMET; 3=44A
940  /REM GEOMETRY
950  /REM FEED RATE
960  /REM  TEST ID NUMBER;1-72;NOTE 1.2 TESTS ARE NEGATIVE
970  /REM  PRIMARY MEASUREMENT FLUTE 1 (IN INCHES)
972  /REM     "         "         "  2 ( "   "   )
974  /REM     "         "         "  3 ( "   "   )
976  /REM     "         "         "  4 ( "   "   )
978  /REM     "         "         "  5 ( "   "   )
980  /REM     "         "         "  6 ( "   "   )
1000  0,1,3,1,2,3,.0055,.002,.003,.006,.007,.006/REM BL OK,5CHP
1010  0,1,3,1,1,-4,.005,.006,.007,.008,.008,.0075/REM BL OK,5CHP
1020  0,1,2,1,1,-12,.007,.006,.0045,.0025,.0025,.005/REM OK
1030  0,1,1,1,1,-9,.003,.002,.0035,.002,.003,.003/REM CHATTER,US
1040  0,1,3,1,1,-13,.003,.004,.003,.003,.003,.003/REM ROUGH FINISH,US
1050  0,1,2,1,1,-16,.006,.004,.0015,.002,.004,.0065/REM 5CHP,PBL
1060  0,1,2,1,2,17,.003,.0025,.0025,.0025,.003,.004/REM P BL,US
1070  0,1,2,1,2,18,.006,.005,.002,.002,.004,.0065/REM 5CHP,INC BL
1080  0,1,1,1,1,-15,.004,.003,.003,.0035,.004,.005/REM BL OK,US

+*
090  0,1,3,1,2,20,.0025,.003,.004,.006,.006,.005/REM P BL
1100  0,1,1,1,2,23,.003,.0025,.003,.003,.003,.0045/REM BL OK,US
1110  0,1,1,1,2,24,.003,.003,.003,.002,.0035,.003/REM LOUSY BL,US
1120  0,1,3,2,2,1,.0065,.009,.006,.007,1E11,1E11/REM BL GD
1130  0,1,2,2,1,-2,.005,.007,.005,.0055,1E11,1E11/REM BL GD
1140  0,1,1,2,2,5,.0055,.008,.005,.006,1E11,1E11 /REM BL GD
1150  0,1,2,2,2,6,.0065,.006,.008,.006,1E11,1E11/REM BL GD
1160  0,1,2,2,2,7,.007,.0055,.006,.006,1E11,1E11/REM BL GD
1170  0,1,3,2,2,8,1E11,1E11,1E11,1E11,1E11,1E11/REM NOT RUN,NO MATL
1180  0,1,1,2,1,-10,.006,.0085,.0065,.006,1E11,1E11/REM BL GD
1190  0,1,3,2,1,-11,.006,.009,.007,.0065,1E11,1E11/REM BL OK
1200  0,1,3,2,1,-14,.0065,.0085,.006,.0065,1E11,1E11/REM BL OK
1210  0,1,1,2,2,15,.006,.0055,.008,.006,1E11,1E11/REM BL GD
1220  0,1,2,2,1,-21,.006,.008,.0055,.0065,1E11,1E11/REM P BL,3CHP
1230  0,1,1,2,1,-22,.006,.007,.007,.006,1E11,1E11/REM P BL,1CHP
1240  0,1,2,2,1,2,.007,.0095,.016,.015,1E11,1E11/REM P BL,2CHP
1250  0,1,3,2,1,11,.006,.006,.008,.0075,1E11,1E11/REM P BL
1260  0,1,2,1,1,12,.017,.0165,.0115,.003,.0105,.012/REM P BL
1270  0,1,3,2,1,14,.0165,.010,.005,.0095,1E11,1E11/REM P BL
1280  0,1,2,1,1,16,.008,.0125,.0145,.016,.011,.0045/REM P BL
1290  0,1,2,2,1,21,.005,.0155,.0155,.0065,1E11,1E11/REM P BL,NS N REGRD
1300  0,1,1,2,1,10,.0055,.0055,.008,.006,1E11,1E11
```

```
**
1310  0,1,1,2,1,22,.005,.007,.005,.006,1E11,1E11
1320  0,1,3,1,1,13,.003,.0025,.003,.0025,.0025,.0035/REM BL GD
1330  0,1,1,1,1,19,.003,.001,.002,.002,.002,.002/REM P BL
1340  0,1,3,1,1,4,.003,.0035,.0035,.0035,.005,.004/REM P BL,5CHP
1350  0,1,1,1,1,9,.0045,.0035,.003,.003,.004,.0035/REM BL OK
1360  1,1,2,2,1,2,.010,.008,.007,.0105,1E11,1E11
1370  2,1,2,2,1,2,.012,.011,.0095,.0115,1E11,1E11/REM 2CHP
1380  1,1,3,2,1,11,.009,.007,.0075,.0085,1E11,1E11/REM BURNING
1390  2,1,3,2,1,11,.013,.010,.008,.010,1E11,1E11/REM ALL CHP
1400  1,1,2,1,1,12,.007,.006,.0055,.0035,.0045,.005/REM 5CHP
1410  2,1,2,1,1,12,.010,.0065,.007,.005,.0065,.0065/REM 5CHP,BURN
1420  1,1,3,2,1,14,.009,.010,.006,.0055,1E11,1E11/REM ALL CHP
1430  2,1,3,2,1,14,.0125,.0115,.008,.008,1E11,1E11/REM ALL CHP
1440  1,1,2,1,1,16,.0065,.0075,.004,.0035,.005,.008/REM 6CHP
1450  2,1,2,1,1,16,.008,.0095,.0095,.007,.008,.009/REM 6CHP
1460  1,1,2,2,1,21,.0095,.0135,.009,.006,1E11,1E11/REM 1,2 CHP
1470  2,1,2,2,1,21,.0105,.016,.0105,.0075,1E11,1E11/REM 1,2,3 CHP
1480  1,1,1,2,1,22,.0115,.010,.004,.010,1E11,1E11/REM 1,2CHP
1490  2,1,1,2,1,22,.015,.014,.008,.013,1E11,1E11/REM 1,2,4CHP
1500  1,1,1,2,1,10,.0105,.008,.010,.009,1E11,1E11/REM 1CHP
1510  2,1,1,2,1,10,.0125,.0145,.015,.013,1E11,1E11/REM 1,3CHP
1520  1,1,1,1,1,9,.007,.0105,.0085,.0045,.003,.004

**
1530  2,1,1,1,1,9,.009,.011,.011,.007,.0055,.006/REM 3CHP
1540  1,1,3,1,1,4,.0085,.011,.010,.0075,.0055,.0055
1550  2,1,3,1,1,4,.0105,.012,.0115,.010,.0075,.007
1560  1,1,1,1,1,19,.011,.008,.007,.004,.0045,.007
1570  2,1,1,1,1,19,.014,.013,.010,.0075,.0065,.0085/REM 1,2CHP
1580  [illegible]
1590  2,1,3,1,1,13,.0105,.016,.010,.007,.007,.009/REM 1,2CHP
1600  1,1,1,2,2,15,.010,.012,.0075,.007,1E11,1E11/REM 1,2 CHP
1610  2,1,1,2,2,15,.0155,.017,.014,.012,1E11,1E11/REM 1,2,3,4CHP
1620  1,1,3,2,1,-11,.0135,.0145,.0085,.0125,1E11,1E11/REM 1 CHP
1630  2,1,3,2,1,-11,.017,.017,.0125,.015,1E11,1E11/REM 1,2,3,4CHP
1640  1,1,3,2,1,-14,.014,.010,.007,.0115,1E11,1E11
1650  2,1,3,2,1,-14,.021,.019,.022,.021,1E11,1E11/REM 1,2,3,4CHP
1660  1,1,2,2,1,-21,.009,.0125,.0055,.005,1E11,1E11
1670  2,1,2,2,1,-21,.014,.015,.0065,.0085,1E11,1E11
1680  1,1,1,2,1,-22,.0105,.012,.0065,.0055,1E11,1E11
1690  2,1,1,2,1,-22,.015,.0165,.017,.014,1E11,1E11
1700  1,1,3,2,2,8,1E11,1E11,1E11,1E11,1E11,1E11/REM NOT RUN
1710  2,1,3,2,2,8,1E11,1E11,1E11,1E11,1E11,1E11/REM NOT RUN
1720  1,1,3,2,2,1,.014,.015,.0075,.012,1E11,1E11/REM 1,2 CHP
1730  2,1,3,2,2,1,.0235,.020,.015,.019,1E11,1E11/REM ALL CHP
1740  1,1,2,2,1,-2,.011,.009,.004,.0055,1E11,1E11
```

```
↑*
1750  2,1,2,2,1,-2,.011,.0125,.006,.0065,1E11,1E11/REM 1,2 CHP
1760  1,1,1,2,1,-10,.010,.009,.006,.007,1E11,1E11
1770  2,1,1,2,1,-10,.015,.0125,.007,.0105,1E11,1E11
1780  1,1,1,2,2,5,.016,.015,.006,.009,1E11,1E11/REM ALL CHP
1790  2,1,1,2,2,5,.019,.018,.0125,.014,1E11,1E11/REM ALL CHP
1800  1,1,2,2,2,6,.008,.009,.0055,.005,1E11,1E11/REM 2 CHP
1810  2,1,2,2,2,6,.0145,.0145,.0115,.0095,1E11,1E11/REM 1,2CHP
1820  1,1,2,2,2,7,.006,.0085,.0055,.004,1E11,1E11/REM 2CHP
1830  2,1,2,2,2,7,.012,.0125,.012,.009,1E11,1E11/REM 2,3,4CHP
1840  1,1,2,1,2,17,.0075,.0085,.013,.018,.008,.007/REM ALLCHP
1850  2,1,2,1,1,17,.0085,.009,.013,.018,.009,.009/REM ALL CHP
1860  1,1,2,1,2,18,.012,.010,.005,.004,.007,.010/REM 1,5,6CHP
1870  2,1,2,1,2,18,.018,.010,.007,.006,.007,.013/REM 1,2,5,6CHP
1880  1,1,1,1,1,-19,.005,.0065,.0075,.008,.0075,.006/REM OK
1890  2,1,1,1,1,-19,.009,.008,.009,.010,.009,.008/REM GD
1900  1,1,3,1,2,20,.0075,.0065,.006,.0075,.0085,.009/REM 1,3CHP
1910  2,1,3,1,2,20,.010,.010,.0085,.010,.011,.012/REM 1,3,6CHP,4BRNT
1920  1,1,1,1,2,23,.006,.0075,.0065,.007,.008,.013/REM 1,2,4,5,6CHP
1930  2,1,1,1,2,23,.009,.011,.013,.0145,.0195,.015/REM ALL CHP
1940  1,1,1,1,2,24,.010,.010,.007,.0095,.008,.010/REM ALL CHP
1950  2,1,1,1,2,24,.014,.011,.0105,.010,.0125,.011/REM ALL CHP
1960  1,1,3,1,2,3,.0095,.008,.007,.0075,.009,.010/REM 5,6 CHP

↑*
1970  2,1,3,1,2,3,.011,.009,.008,.009,.011,.010/REM 1,5,6 CHP
1980  1,1,3,1,1,-4,.008,.010,.009,.010,.0075,.010/REM 2,5CHP
1990  2,1,3,1,1,-4,.011,.0105,.0095,.010,.0105,.0105/REM 2CHP
2000  1,1,2,1,1,-12,.012,.008,.005,.005,.008,.009/REM 5CHP
2010  2,1,2,1,1,-12,.014,.009,.005,.005,.008,.010/REM 1,5,6CHP
2020  1,1,1,1,1,-9,.007,.007,.006,.0055,.008,.0075/REM REGRD OD
2030  2,1,1,1,1,-9,.010,.0095,.0095,.0075,.008,.0085/REM BURNING
2040  1,1,3,1,1,-13,.009,.0085,.0075,.007,.010,.011/REM REGRD OD
2050  2,1,3,1,1,-13,.011,.010,.009,.0085,.0105,.011/REM BURNING
2060  1,1,2,1,1,-16,.010,.0075,.004,.004,.0075,.008/REM 1,5 CHP
2070  2,1,2,1,1,-16,.011,.010,.005,.005,.0075,.0105/REM BURNING
2080  1,2,2,1,2,38,.006,.005,.0055,.0065,.006,.007/REM ALL CHIP
2090  2,2,2,1,2,38,.0065,.006,.0065,.0075,.006,.0075/REM ALL CHIP  BURN
2100  1,2,1,1,1,44,.0055,.007,.0075,.007,.0065,.007/REM EXC CHIP BURN
2110  1,2,1,1,1,44,.009,.007,.008,.008,.0105,.011/REM ALL CHIP BURN
2120  1,2,3,1,1,35,.0055,.007,.008,.0075,.011,.005/REM ALL CHIP BURN
2130  2,2,3,1,1,35,.0085,.0085,.009,.010,.011,.0065/REM ALL CHIP MAX BURN
2140  1,2,3,1,2,48,.0058,.0035.003,.0025,.003,.0035/REM
2150  2,2,3,1,2,48,.006,.0035,.0045,.0042,.0043,.0035/REM
2160  1,2,2,1,2,37,.0035,.0035,.0035,.0045,.0035,.0035/REM
2170  2,2,2,1,2,37,.004,.004,.005,.0068,.005,.0045/REM
2180  1,2,2,1,1,36,.0055,.006,.0063,.006,.004,.005/REM EXC BURN
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2190  2,2,2,1,1,36,.007,.008,.008,.0075,.0065,.0075/REM EXC CHIP MAX BURN
2200  1,2,1,1,1,30,.003,.004,.003,.0035,.0045,.0045/REM BURNING
2210  2,2,1,1,1,30,.005,.006,.004,.004,.005,.005/REM BURNING
2220  1,2,1,1,2,31,.0045,.0045,.0045,.0055,.0045,.005/REM MIN BURN
2230  2,2,1,1,2,31,.0055,.0055,.007,.007,.0065,.006/REM MIN BURN
2240  1,2,3,1,1,39,.005,.0045,.004,.0045,.0055,.005/REM BURNING
2250  2,2,3,1,1,39,.007,.006,.0055,.0055,.0065,.0065/REM BURN VRY DULL
2260  1,2,3,1,2,45,.004,.003,.004,.0045,.003,.004/REM MIN BURN
2270  2,2,3,1,2,45,.0055,.0085,.0065,.0095,.0065,.008/REM NOSE WEAR
2280  1,2,1,1,2,25,.0045,.0035,.004,.0055,.0045,.0045/REM
2290  2,2,1,1,2,25,.0056,.0056,.005,.0062,.0058,.0068/REM
2300  1,2,2,1,1,46,.005,.008,.010,.022,.009,.0115/REM FLUTE 2,6 MISSING
2310  2,2,2,1,1,46,1E11,1E11,1E11,1E11,1E11,1E11/REM NOT RUN
2320  1,2,2,2,1,28,.006,.0055,.0065,.0055,1E11,1E11/REM MAX BURN
2330  2,2,2,2,1,28,.014,.0145,.0135,.019,1E11,1E11/REM     "   EXT NOSE CHIP
2340  1,2,2,2,2,32,.0085,.009,.014,.0105,1E11,1E11/REM BURN
2345  2,2,2,2,2,32,.015,.0135,.0145,.011,1E11,1E11
2350  1,2,2,2,1,42,.011,.0115,.012,.012,1E11,1E11/REM DULL,CHP NOSE / BURN
2360  1,2,3,2,1,27,.010,.0085,.010,.010,1E11,1E11/REM BURN EXC NOSE CHIP
2370  2,2,3,2,1,27,.012,.010,.011,.0125,1E11,1E11/REM  "    "    "    "
2380  1,2,1,2,2,26,.008,.008,.008,.007,1E11,1E11 /REM MIN CHIP NOSE
2390  2,2,1,2,2,26,.010,.0125,.009,.009,1E11,1E11/REM     "

**
400  1,2,3,2,2,29,.010,.011,.0115,.0105,1E11,1E11 /REM DULL NOSE / BURN
2410  2,2,3,2,2,29,.016,.0115,.0145,.0115,1E11,1E11/REM FAIL THIS PK
2420  1,2,3,2,2,33,.009,.007,.007,.0085,1E11,1E11 /REM DULL NOSE / BURN
2430  2,2,3,2,2,33,.0125,.009,.0095,.011,1E11,1E11/REM        "
2450  2,2,2,2,1,42,.0115,.0115,.015,.015,1E11,1E11/REM VRY DL, ALLCHP, MAXBURN
2460  1,2,1,2,1,40,.008,.0105,.009,.0085,1E11,1E11 /REM SOME BURN
2470  2,2,1,2,1,40,.008,.011,.0105,.011,1E11,1E11/REM MAX BURN/EXC NOSE CHP
2480  1,2,1,2,2,41,.0075,.008,.0095,.0075,1E11,1E11/REM MIN CHP,BURN
2490  2,2,1,2,2,41,.010,.010,.0125,.0105,1E11,1E11/REM     "   ,MORE BURN
2500  1,2,1,2,1,47,.008,.0145,.0095,.0125,1E11,1E11 /REM SOME BURN
2510  2,2,1,2,1,47,.0145,.0165,.0125,.0125,1E11,1E11/REM CHP NOSE/MAX BURN
2520  1,2,3,2,1,34,.012,.014,.0135,.0125,1E11,1E11/REM FLT 1,3,4 EX CHP/BURN
2530  2,2,3,2,1,34,.0125,.0255,.020,.0185,1E11,1E11/REM           "
2540  1,2,2,2,2,43,.0135,.012,.0085,.0085,1E11,1E11 /REM MAX NOSE WEAR/BURN
2550  2,2,2,2,2,43,.015,.014,.010,.0095,1E11,1E11/REM     "   /MORE BURN
2560  0,2,2,2,1,28,.004,.0045,.0035,.0045,1E11,1E11/REM CHPYRAD,PBL
2570  0,2,2,2,2,32,.008,.0085,.006,.007,1E11,1E11/REM NO SEC1,4
2580  0,2,3,2,1,27,.005,.006,.007,.006,1E11,1E11/REM "
2590  0,2,1,2,2,26,.0065,.006,.0045,.0055,1E11,1E11
2600  0,2,3,2,2,29,.008,.0095,.012,.0065,1E11,1E11
2610  0,2,3,2,2,33,.0075,.005,.005,.006,1E11,1E11
2620  0,2,2,2,1,42,.006,.008,.011,.010,1E11,1E11
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**
630  0,2,1,2,1,40,.005,.0045,.0045,.0055,1E11,1E11
2640  0,2,1,2,2,41,.0045,.0055,.008,.0055,1E11,1E11
2650  0,2,1,2,1,47,.006,.0055,.003,.0045,1E11,1E11
2660  0,2,3,2,1,34,.0055,.0015,.0075,.008,1E11,1E11
2670  0,2,2,2,2,43,.0055,.0105,.008,.006,1E11,1E11
2680  0,2,1,1,2,25,.004,.0035,.005,.006,.005,.005
2690  0,2,1,1,1,30,.0035,.0025,.002,.002,.0035,.003
2700  0,2,1,1,2,31,.0025,.0025,.003,.004,.0035,.0035
2710  0,2,3,1,1,35,.0045,.005,.009,.004,.0045,.000
2720  0,2,2,1,1,36,.0058,.0045,.0062,.0031,.0028,.0052
2730  0,2,2,1,2,37,.002,.002,.003,.0035,.0035,.0029
2740  0,2,2,1,2,38,.[illegible],.0055,.0039,.0035,.0005,.[illegible]   .0055 .0045 .0045 .0055
                                                                        .0055 .005
2750  0,2,3,1,1,39,.003,.0055,.002,.002,.001,.003
2760  0,2,1,1,1,44,.0095,.0045,.0035,.0065,.012,.0125
2770  0,2,3,1,2,45,.003,.0085,.005,.010,.003,.008
2780  0,2,2,1,1,46,.0045,.0035,.0025,.0025,.0025,.004
2790  0,2,3,1,2,48,.0045,.002,.003,.002,.003,.0025
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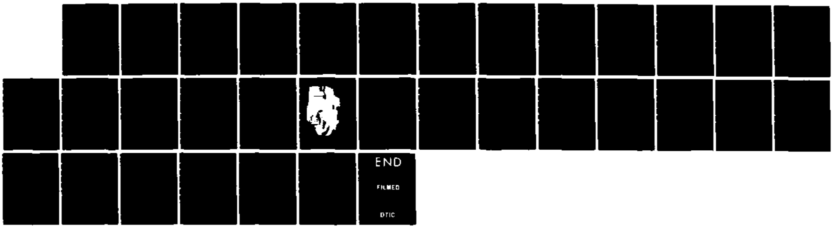
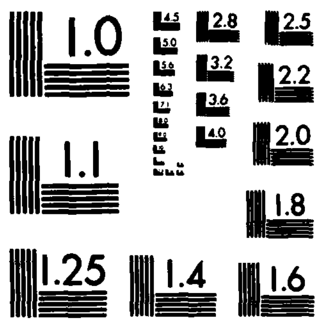
AD-A150 450 T700 CUTTER LIFE IMPROVEMENT PROGRAM(U) GENERAL ELECTRIC CO LYNN MA AIRCRAFT ENGINE BUSINESS GROUP D M DOMBROWSKI MAR 84 R84AEB010 DAAK50-81-C-0029 2/2

UNCLASSIFIED F/G 13/9 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

APPENDIX E

SUPPORT DATA FOR LABORATORY CUTTER WEAR EVALUATION PROGRAM

This Appendix contains supporting data for the statistical analysis of the Laboratory Cutter Wear Evaluation. The raw data, statistical averages, ranges, standard deviation, sum of the wear, high and low wear flutes are shown for each cutter diameter.

APPENDIX E

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	LIST (T1)		T	M	G	F	FLANK WEAR (MILS) ON FLUTE						
	01	0	.1	.1	.1	.1	.0030	.0010	.0020	.0020	.0020	.0020	
	02	0	.1	.1	.1	.1	.0045	.0035	.0030	.0030	.0040	.0035	
	03	1	.1	.1	.1	.1	.0070	.0105	.0085	.0045	.0030	.0040	19
	04	2	.1	.1	.1	.1	.0090	.0110	.0110	.0070	.0055	.0060	
	05	1	.1	.1	.1	.1	.0110	.0080	.0070	.0040	.0045	.0070	
	06	2	.1	.1	.1	.1	.0140	.0130	.0100	.0075	.0065	.0085	
	07	0	.1	.1	.2	.1	.0055	.0055	.0050	.0050			
	08	0	.1	.1	.2	.1	.0050	.0070	.0050	.0060			
	09	1	.1	.1	.2	.1	.0115	.0100	.0040	.0100			5
	10	2	.1	.1	.2	.1	.0150	.0140	.0080	.0130			
	11	1	.1	.1	.2	.1	.0105	.0080	.0100	.0090			
	12	2	.1	.1	.2	.1	.0125	.0145	.0150	.0130			
	13	0	.1	.2	.1	.1	.0170	.0165	.0115	.0030	.0105	.0120	
	14	0	.1	.2	.1	.1	.0080	.0125	.0145	.0160	.0110	.0045	
	15	1	.1	.2	.1	.1	.0070	.0060	.0055	.0035	.0045	.0050	
	16	2	.1	.2	.1	.1	.0100	.0065	.0070	.0050	.0065	.0065	26
	17	1	.1	.2	.1	.1	.0065	.0075	.0040	.0035	.0050	.0080	
	18	2	.1	.2	.1	.1	.0080	.0095	.0095	.0070	.0080	.0090	
	19	2	.1	.2	.1	.1	.0085	.0090	.0130	.0180	.0090	.0090	
	20	0	.1	.2	.2	.1	.0070	.0095	.0160	.0150			
	21	0	.1	.2	.2	.1	.0050	.0155	.0155	.0065			61
F1	22	1	.1	.2	.2	.1	.0100	.0080	.0070	.0105			
	23	2	.1	.2	.2	.1	.0120	.0110	.0095	.0115			
	24	1	.1	.2	.2	.1	.0095	.0135	.0090	.0060			
	25	2	.1	.2	.2	.1	.0105	.0160	.0105	.0075			
	26	0	.1	.3	.1	.1	.0030	.0025	.0030	.0025	.0025	.0035	
	27	0	.1	.3	.1	.1	.0030	.0035	.0035	.0035	.0050	.0040	
	28	1	.1	.3	.1	.1	.0085	.0110	.0100	.0075	.0055	.0055	10
	29	2	.1	.3	.1	.1	.0105	.0120	.0115	.0100	.0075	.0070	
	30	1	.1	.3	.1	.1	.0090	.0100	.0080	.0040	.0030	.0055	
	31	2	.1	.3	.1	.1	.0105	.0160	.0100	.0070	.0070	.0090	
	32	0	.1	.3	.2	.1	.0060	.0060	.0080	.0075			
	33	0	.1	.3	.2	.1	.0165	.0100	.0050	.0095			
	34	1	.1	.3	.2	.1	.0090	.0070	.0075	.0085			25
	35	2	.1	.3	.2	.1	.0130	.0100	.0080	.0100			
	36	1	.1	.3	.2	.1	.0090	.0100	.0060	.0055			
	37	2	.1	.3	.2	.1	.0125	.0115	.0080	.0080			
	38	0	.1	.1	.1	.2	.0030	.0025	.0030	.0030	.0030	.0045	
	39	0	.1	.1	.1	.2	.0030	.0030	.0630	.0020	.0035	.0030	
	40	1	.1	.1	.1	.2	.0060	.0075	.0065	.0070	.0080	.0130	72
	41	2	.1	.1	.1	.2	.0090	.0110	.0130	.0145	.0195	.0150	
	42	1	.1	.1	.1	.2	.0100	.0100	.0070	.0095	.0060	.0100	
	43	2	.1	.1	.1	.2	.0140	.0110	.0105	.0100	.0125	.0110	
	44	0	.1	.1	.2	.2	.0055	.0080	.0050	.0060			
	45	0	.1	.1	.2	.2	.0060	.0055	.0080	.0060			11
	46	1	.1	.1	.2	.2	.0100	.0120	.0075	.0070			
	47	2	.1	.1	.2	.2	.0155	.0170	.0140	.0120			
	48	1	.1	.1	.2	.2	.0160	.0150	.0060	.0090			
	49	2	.1	.1	.2	.2	.0190	.0180	.0125	.0140			
	50	0	.1	.2	.1	.2	.0030	.0025	.0025	.0025	.0030	.0040	
	51	0	.1	.2	.1	.2	.0060	.0050	.0020	.0020	.0040	.0065	37
F2	52	1	.1	.2	.1	.2	.0075	.0085	.0130	.0180	.0080	.0070	
	53	1	.1	.2	.1	.2	.0120	.0100	.0050	.0040	.0070	.0100	
	54	2	.1	.2	.1	.2	.0180	.0100	.0070	.0060	.0070	.0130	

55	0	,1	,2	,2	,2	,.0065	,.0060	,.0080	,.0060	,		
56	0	,1	,2	,2	,2	,.0070	,.0055	,.0060	,.0060	,		
57	1	,1	,2	,2	,2	,.0080	,.0090	,.0055	,.0050	,		13
58	2	,1	,2	,2	,2	,.0145	,.0145	,.0115	,.0095	,		
59	1	,1	,2	,2	,2	,.0060	,.0085	,.0055	,.0040	,		
60	2	,1	,2	,2	,2	,.0120	,.0125	,.0120	,.0090	,		
61	0	,1	,3	,1	,2	,.0055	,.0020	,.0030	,.0060	,.0070	,.0060 ,	
62	0	,1	,3	,1	,2	,.0025	,.0030	,.0040	,.0060	,.0060	,.0050 ,	
63	1	,1	,3	,1	,2	,.0075	,.0065	,.0060	,.0075	,.0085	,.0090 ,	9
64	2	,1	,3	,1	,2	,.0100	,.0100	,.0085	,.0100	,.0110	,.0120 ,	
65	1	,1	,3	,1	,2	,.0095	,.0080	,.0070	,.0075	,.0090	,.0100 ,	
66	2	,1	,3	,1	,2	,.0110	,.0090	,.0080	,.0090	,.0110	,.0100 ,	
67	0	,1	,3	,2	,2	,.0065	,.0090	,.0060	,.0070	,		
68	1	,1	,3	,2	,2	,.0140	,.0150	,.0075	,.0120	,		1
69	2	,1	,3	,2	,2	,.0235	,.0200	,.0150	,.0190	,		

LSET T2 [illegible] 11 MAY 1983

		T	M	G	F							
01	1	,2	,1	,1	,1	,.0055	,.0070	,.0075	,.0070	,.0065	,.0070 ,	
02	1	,2	,1	,1	,1	,.0090	,.0070	,.0080	,.0080	,.0105	,.0110 ,	
03	1	,2	,1	,1	,1	,.0030	,.0040	,.0020	,.0035	,.0045	,.0045 ,	
04	2	,2	,1	,1	,1	,.0050	,.0060	,.0040	,.0040	,.0050	,.0050 ,	34
05	0	,2	,1	,1	,1	,.0035	,.0025	,.0020	,.0020	,.0035	,.0030 ,	
06	0	,2	,1	,1	,1	,.0075	,.0045	,.0025	,.0065	,.0120	,.0125 ,	
07	1	,2	,1	,2	,1	,.0050	,.0105	,.0090	,.0085	,		
08	2	,2	,1	,2	,1	,.0080	,.0110	,.0105	,.0110	,		
09	1	,2	,1	,2	,1	,.0080	,.0145	,.0095	,.0125	,		7•
10	2	,2	,1	,2	,1	,.0145	,.0165	,.0125	,.0125	,		
11	0	,2	,1	,2	,1	,.0050	,.0045	,.0045	,.0055	,		
12	0	,2	,1	,2	,1	,.0060	,.0055	,.0030	,.0045	,		
13	1	,2	,2	,1	,1	,.0055	,.0060	,.0063	,.0060	,.0040	,.0050 ,	
14	2	,2	,2	,1	,1	,.0070	,.0080	,.0080	,.0075	,.0065	,.0075 ,	
15	1	,2	,2	,1	,1	,.0050	,.0080	,.0100	,.0220	,.0090	,.0115 ,	49
16	0	,2	,2	,1	,1	,.0058	,.0045	,.0062	,.0031	,.0028	,.0052 ,	
17	0	,2	,2	,1	,1	,.0045	,.0035	,.0025	,.0025	,.0025	,.0040 ,	
18	1	,2	,2	,2	,1	,.0060	,.0055	,.0065	,.0055	,		
19	2	,2	,2	,2	,1	,.0140	,.0145	,.0135	,.0190	,		
20	1	,2	,2	,2	,1	,.0110	,.0115	,.0120	,.0120	,		
21	2	,2	,2	,2	,1	,.0115	,.0115	,.0150	,.0150	,		12
22	0	,2	,2	,2	,1	,.0040	,.0045	,.0035	,.0045	,		
23	0	,2	,2	,2	,1	,.0060	,.0080	,.0110	,.0100	,		
24	1	,2	,3	,1	,1	,.0055	,.0070	,.0090	,.0075	,.0110	,.0050 ,	
25	2	,2	,3	,1	,1	,.0085	,.0085	,.0090	,.0100	,.0110	,.0065 ,	
26	1	,2	,3	,1	,1	,.0050	,.0045	,.0040	,.0045	,.0055	,.0050 ,	47
27	2	,2	,3	,1	,1	,.0070	,.0060	,.0055	,.0055	,.0065	,.0065 ,	
28	0	,2	,3	,1	,1	,.0045	,.0050	,.0090	,.0040	,.0045	,.0000 ,	
29	0	,2	,3	,1	,1	,.0030	,.0055	,.0020	,.0020	,.0010	,.0030 ,	
30	1	,2	,3	,2	,1	,.0100	,.0085	,.0100	,.0100	,		
31	2	,2	,3	,2	,1	,.0120	,.0100	,.0110	,.0125	,		
32	1	,2	,3	,2	,1	,.0120	,.0140	,.0135	,.0125	,		67
33	2	,2	,3	,2	,1	,.0125	,.0255	,.0200	,.0185	,		
34	0	,2	,3	,2	,1	,.0050	,.0060	,.0070	,.0060	,		
35	0	,2	,3	,2	,1	,.0055	,.0015	,.0075	,.0080	,		

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36	1	,2	,1	,1	,2	,.0945	,.0045	,.0045	,.0055	,.0045	,.0050 ,	
37	2	,2	,1	,1	,2	,.0055	,.0055	,.0070	,.0070	,.0065	,.0060 ,	
38	1	,2	,1	,1	,2	,.0045	,.0035	,.0040	,.0055	,.0045	,.0048 ,	φ2
39	2	,2	,1	,1	,2	,.0056	,.0056	,.0050	,.0062	,.0058	,.0068 ,	
40	0	,2	,1	,1	,2	,.0040	,.0035	,.0050	,.0060	,.0050	,.0050 ,	
41	0	,2	,1	,1	,2	,.0025	,.0025	,.0030	,.0040	,.0035	,.0035 ,	
42	1	,2	,1	,2	,2	,.0080	,.0080	,.0080	,.0070 ,			
43	2	,2	,1	,2	,2	,.0100	,.0125	,.0090	,.0090 ,			
44	1	,2	,1	,2	,2	,.0075	,.0080	,.0095	,.0075 ,			
45	2	,2	,1	,2	,2	,.0100	,.0100	,.0125	,.0105 ,			φ4
46	0	,2	,1	,2	,2	,.0065	,.0060	,.0045	,.0055 ,			
47	0	,2	,1	,2	,2	,.0045	,.0055	,.0080	,.0055 ,			
48	1	,2	,2	,1	,2	,.0060	,.0050	,.0055	,.0065	,.0060	,.0070 ,	
49	2	,2	,2	,1	,2	,.0065	,.0060	,.0065	,.0075	,.0060	,.0075 ,	50
50	1	,2	,2	,1	,2	,.0035	,.0035	,.0035	,.0045	,.0035	,.0035 ,	
51	2	,2	,2	,1	,2	,.0040	,.0040	,.0050	,.0068	,.0050	,.0045 ,	
52	0	,2	,2	,1	,2	,.0020	,.0020	,.0030	,.0035	,.0035	,.0029 ,	
53	0	,2	,2	,1	,2	,.0045	,.0055	,.0039	,.0035	,.0035	,.0038 ,	
54	1	,2	,2	,2	,2	,.0085	,.0090	,.0140	,.0105 ,			
55	2	,2	,2	,2	,2	,.0150	,.0135	,.0145	,.0110 ,			
56	1	,2	,2	,2	,2	,.0135	,.0120	,.0085	,.0085 ,			4/
57	2	,2	,2	,2	,2	,.0150	,.0140	,.0100	,.0095 ,			
58	0	,2	,2	,2	,2	,.0080	,.0085	,.0060	,.0070 ,			
59	1	,2	,3	,1	,2	,.0058	,.0035	,.0030	,.0025	,.0030	,.0035 ,	
60	2	,2	,3	,1	,2	,.0060	,.0035	,.0045	,.0042	,.0043	,.0035 ,	7/
61	1	,2	,3	,1	,2	,.0040	,.0030	,.0040	,.0045	,.0030	,.0040 ,	
62	2	,2	,3	,1	,2	,.0055	,.0085	,.0065	,.0095	,.0065	,.0080 ,	
63	0	,2	,3	,1	,2	,.0030	,.0085	,.0050	,.0100	,.0030	,.0080 ,	
64	1	,2	,3	,2	,2	,.0100	,.0110	,.0115	,.0105 ,			
65	2	,2	,3	,2	,2	,.0160	,.0115	,.0145	,.0115 ,			
66	1	,2	,3	,2	,2	,.0090	,.0070	,.0070	,.0085 ,			24
67	2	,2	,3	,2	,2	,.0125	,.0090	,.0095	,.0110 ,			
68	0	,2	,3	,2	,2	,.0080	,.0095	,.0120	,.0065 ,			
69	0	,2	,3	,2	,2	,.0075	,.0050	,.0050	,.0060 ,			

APPENDIX E

BRN 81-6
/nl (T/A) (-)

2nd Data

CALULATE STATISTICS FOR: ROWS 1; COLUMNS 2; BOTH 3?3

28 JUN 1983

ROW STATISTICS:-

AVG.	RANGE	S	SUM	HI	LO
.0062	.0075	.0029	.0375	.0105	.0030
.0082	.0055	.0024	.0495	.0110	.0055
.0069	.0070	.0025	.0415	.0110	.0040
.0099	.0075	.0030	.0595	.0140	.0065
.0052	.0035	.0012	.0315	.0070	.0035
.0069	.0050	.0017	.0415	.0100	.0050
.0057	.0045	.0019	.0345	.0080	.0035
.0085	.0025	.0010	.0510	.0095	.0070
.0080	.0055	.0023	.0480	.0110	.0055
.0097	.0050	.0021	.0585	.0120	.0070
.0066	.0070	.0028	.0395	.0100	.0030
.0099	.0090	.0033	.0595	.0160	.0070
.0080	.0070	.0025	.0480	.0130	.0060
.0137	.0105	.0036	.0820	.0195	.0090
.0091	.0030	.0013	.0545	.0100	.0070
.0115	.0040	.0015	.0690	.0140	.0100
.0103	.0110	.0043	.0620	.0180	.0070
.0080	.0080	.0032	.0483	.0120	.0040
.0102	.0120	.0046	.0610	.0180	.0060
.0109	.0095	.0037	.0655	.0190	.0095
.0075	.0030	.0011	.0450	.0090	.0060
.0102	.0035	.0012	.0615	.0120	.0085
.0085	.0030	.0012	.0510	.0100	.0070
.0097	.0030	.0012	.0580	.0110	.0090

COLUMN STATISTICS:-

AVG.	RANGE	STD.DEV.	SUM	HI	LO
.0097	.0120	.0027	.2340	.0180	.0060
.0096	.0100	.0022	.2315	.0160	.0060
.0086	.0090	.0025	.2055	.0130	.0040
.0080	.0145	.0040	.1915	.0180	.0035
.0077	.0165	.0035	.1850	.0185	.0020
.0087	.0110	.0028	.2100	.0150	.0040

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CALULATE STATISTICS FOR: ROWS 1; COLUMNS 2; BOTH 3?3

ROW STATISTICS:-

AVG.	RANGE	S	SUM	HI	LO
.0067	.0020	.0007	.0405	.0075	.0055
.0089	.0040	.0016	.0535	.0110	.0070
.0037	.0015	.0007	.0225	.0045	.0030
.0048	.0020	.0008	.0290	.0060	.0040
.0055	.0023	.0009	.0328	.0063	.0040
.0074	.0015	.0006	.0445	.0080	.0065
.0109	.0170	.0059	.0655	.0220	.0050
.0073	.0060	.0021	.0440	.0110	.0050
.0089	.0045	.0015	.0535	.0110	.0065
.0047	.0015	.0005	.0285	.0055	.0040
.0062	.0015	.0006	.0370	.0070	.0055
.0047	.0010	.0004	.0285	.0055	.0045
.0062	.0015	.0007	.0375	.0070	.0055
.0045	.0020	.0007	.0268	.0055	.0035
.0058	.0018	.0006	.0350	.0068	.0050
.0060	.0020	.0007	.0360	.0070	.0050
.0067	.0015	.0007	.0400	.0075	.0060
.0037	.0010	.0004	.0220	.0045	.0035
.0049	.0028	.0010	.0293	.0065	.0040
.0035	.0033	.0012	.0213	.0058	.0025
.0043	.0025	.0009	.0260	.0060	.0035
.0037	.0015	.0006	.0225	.0045	.0030
.0074	.0049	.0015	.0445	.0095	.0055

COLUMN STATISTICS:-

AVG.	RANGE	STD.DEV.	SUM	HI	LO
.0055	.0060	.0014	.1274	.0090	.0030
.0056	.0055	.0017	.1281	.0085	.0030
.0058	.0070	.0020	.1323	.0100	.0030
.0068	.0195	.0038	.1557	.0220	.0025
.0060	.0080	.0023	.1386	.0110	.0030
.0060	.0080	.0021	.1386	.0115	.0035

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ROW STATISTICS:-

AVG.	RANGE	S	SUM	HI	LO
.0085	.0045	.0020	.0340	.0100	.0055
.0107	.0030	.0013	.0430	.0125	.0095
.0082	.0035	.0014	.0330	.0100	.0065
.0107	.0040	.0018	.0430	.0125	.0085
.0129	.0045	.0019	.0515	.0155	.0110
.0115	.0065	.0029	.0460	.0140	.0075
.0100	.0085	.0035	.0400	.0140	.0055
.0118	.0055	.0028	.0355	.0145	.0090
.0110	.0035	.0015	.0440	.0130	.0095

COLUMN STATISTICS:-

AVG.	RANGE	STD.DEV.	SUM	HI	LO
.0081	.0055	.0019	.0725	.0110	.0055
.0106	.0060	.0019	.0850	.0140	.0080
.0127	.0060	.0020	.1140	.0155	.0095
.0109	.0040	.0013	.0985	.0125	.0085

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CALULATE STATISTICS FOR: ROWS 1; COLUMNS 2; BOTH 3??

ROW STATISTICS:-

AVG.	RANGE	S	SUM	HI	LO
.0089	.0075	.0033	.0355	.0115	.0040
.0125	.0070	.0031	.0500	.0150	.0080
.0094	.0025	.0011	.0375	.0105	.0080
.0137	.0025	.0012	.0550	.0150	.0125
.0089	.0035	.0017	.0355	.0105	.0070
.0110	.0025	.0011	.0440	.0120	.0095
.0095	.0075	.0031	.0380	.0135	.0060
.0111	.0085	.0035	.0445	.0160	.0075
.0080	.0020	.0009	.0320	.0090	.0070
.0102	.0050	.0021	.0410	.0130	.0080
.0076	.0045	.0022	.0305	.0100	.0055
.0100	.0045	.0023	.0400	.0125	.0080
.0091	.0050	.0023	.0365	.0120	.0070
.0146	.0050	.0021	.0585	.0170	.0120
.0115	.0100	.0048	.0460	.0160	.0060
.0159	.0065	.0031	.0635	.0190	.0125
.0069	.0040	.0019	.0275	.0090	.0050
.0125	.0050	.0024	.0500	.0145	.0095
.0060	.0045	.0019	.0240	.0085	.0040
.0114	.0035	.0016	.0455	.0125	.0090
.0121	.0075	.0033	.0485	.0150	.0075
.0194	.0085	.0035	.0775	.0235	.0150

COLUMN STATISTICS:-

AVG.	RANGE	STD.DEV.	SUM	HI	LO
.0124	.0175	.0039	.2735	.0235	.0060
.0125	.0130	.0035	.2750	.0200	.0070
.0091	.0110	.0032	.1995	.0150	.0040
.0097	.0150	.0034	.2130	.0190	.0040

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APPENDIX E

CALULATE STATISTICS FOR: ROWS 1: COLUMNS 2: BOTH 3?3

ROW STATISTICS:-

AVG.	RANGE	S	SUM	HI	LO
.0090	.0025	.0011	.0360	.0105	.0080
.0101	.0030	.0014	.0405	.0110	.0080
.0111	.0065	.0029	.0445	.0145	.0080
.0140	.0040	.0019	.0560	.0165	.0125
.0059	.0010	.0005	.0235	.0065	.0055
.0152	.0055	.0025	.0610	.0190	.0135
.0116	.0010	.0005	.0465	.0120	.0110
.0132	.0035	.0020	.0530	.0150	.0115
.0096	.0015	.0007	.0385	.0100	.0085
.0114	.0025	.0011	.0455	.0125	.0100
.0130	.0020	.0009	.0520	.0140	.0120
.0191	.0130	.0053	.0765	.0255	.0125
.0077	.0010	.0005	.0310	.0080	.0070
.0101	.0035	.0017	.0405	.0125	.0090
.0081	.0020	.0009	.0325	.0095	.0075
.0107	.0025	.0012	.0430	.0125	.0100
.0105	.0055	.0025	.0420	.0140	.0085
.0135	.0040	.0019	.0540	.0150	.0110
.0106	.0050	.0025	.0425	.0135	.0085
.0121	.0055	.0028	.0495	.0150	.0095
.0107	.0015	.0006	.0430	.0115	.0100
.0134	.0045	.0022	.0535	.0160	.0115
.0079	.0020	.0010	.0315	.0090	.0070
.0105	.0035	.0016	.0420	.0125	.0090

COLUMN STATISTICS:-

AVG.	RANGE	STD.DEV.	SUM	HI	LO
.0109	.0160	.0028	.2625	.0160	.0060
.0116	.0200	.0040	.2790	.0255	.0055
.0113	.0135	.0031	.2715	.0200	.0065
.0110	.0135	.0032	.2645	.0190	.0055

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ROW STATISTICS:-

AVG.	RANGE	S	SUM	HI	LO
.0320	.0100	.0071	.0640	.0370	.0270
.0430	.0050	.0035	.0860	.0455	.0405
.0175	.0020	.0014	.0350	.0185	.0165
.0202	.0015	.0011	.0405	[illegible]	.0195
.0175	.0080	.0057	.0350	.0215	.0135
.0225	.0050	.0035	.0450	.0250	.0200
.0228	.0155	.0110	.0455	.0305	.0150
.0525	.0000	.0000	.0525	.0525	.0525

COLUMN STATISTICS:-

AVG.	RANGE	STD.DEV.	SUM	HI	LO
.0264	.0390	.0146	.2115	.0525	.0135
.0274	.0240	.0089	.1920	.0405	.0165

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APPENDIX E

LIST T1-4-6

		1	2	3	4	5	6	
01	24,							
03		.0070	,.0105	,.0085	,.0045	,.0030	,.0040	,19
04		.0090	,.0110	,.0110	,.0070	,.0055	,.0060	,41
05		.0110	,.0080	,.0070	,.0040	,.0045	,.0070	,10
06		.0140	,.0130	,.0100	,.0075	,.0065	,.0085	,41
15		.0070	,.0060	,.0055	,.0035	,.0045	,.0050	,[illegible]
16		.0100	,.0065	,.0070	,.0050	,.0065	,.0065	,[illegible]
17		.0065	,.0075	,.0040	,.0035	,.0050	,.0080	,[illegible]
18		.0080	,.0095	,.0095	,.0070	,.0080	,.0090	,[illegible]
28		.0085	,.0110	,.0100	,.0075	,.0055	,.0055	,[illegible]
29		.0105	,.0120	,.0115	,.0100	,.0075	,.0070	,[illegible]
30		.0090	,.0100	,.0080	,.0040	,.0030	,.0055	,[illegible]
31		.0105	,.0160	,.0100	,.0070	,.0070	,.0090	,[illegible]
40		.0060	,.0075	,.0065	,.0070	,.0080	,.0130	,[illegible]
41		.0090	,.0110	,.0130	,.0145	,.0195	,.0150	,[illegible]
42		.0100	,.0100	,.0070	,.0095	,.0080	,.0100	,[illegible]
43		.0140	,.0110	,.0105	,.0100	,.0125	,.0110	,[illegible]
52		.0075	,.0085	,.0130	,.0180	,.0080	,.0070	,[illegible]
53		.0120	,.0100	,.0050	,.0040	,.0070	,.0100	,[illegible]
54		.0180	,.0100	,.0070	,.0060	,.0070	,.0130	,[illegible]
55		.0085	,.0090	,.0120	,.0180	,.0090	,.0090	,[illegible]
63		.0075	,.0065	,.0060	,.0075	,.0085	,.0090	,9
64		.0100	,.0100	,.0085	,.0100	,.0110	,.0120	,59
65		.0095	,.0080	,.0070	,.0075	,.0090	,.0100	,9
66		.0110	,.0090	,.0080	,.0090	,.0110	,.0100	,[illegible]

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LIST T2-4-6

01  23,6
02  .0055 ,.0070 ,.0075 ,.0070 ,.0065 ,.0070 ,54
03  .0090 ,.0070 ,.0080 ,.0080 ,.0105 ,.0110 ,60
04  .0030 ,.0040 ,.0030 ,.0035 ,.0045 ,.0045 ,34
05  .0050 ,.0060 ,.0040 ,.0040 ,.0050 ,.0050 ,60
06  .0055 ,.0060 ,.0063 ,.0060 ,.0040 ,.0050 ,49
07  .0070 ,.0080 ,.0080 ,.0075 ,.0065 ,.0075 ,65
08  .0050 ,.0080 ,.0100 ,.0220 ,.0090 ,.0115 ,49
09  .0055 ,.0070 ,.0080 ,.0075 ,.0110 ,.0050 ,47
10  .0085 ,.0085 ,.0090 ,.0100 ,.0110 ,.0065 ,[illegible]
11  .0050 ,.0045 ,.0040 ,.0045 ,.0055 ,.0050 ,[illegible]
12  .0070 ,.0060 ,.0055 ,.0055 ,.0065 ,.0065 ,55
13  .0045 ,.0045 ,.0045 ,.0055 ,.0045 ,.0050 ,[illegible]
14  .0055 ,.0055 ,.0070 ,.0070 ,.0065 ,.0060 ,35
15  .0045 ,.0035 ,.0040 ,.0055 ,.0045 ,.0048 ,[illegible]
16  .0056 ,.0056 ,.0050 ,.0062 ,.0058 ,.0068 ,38
17  .0060 ,.0050 ,.0055 ,.0065 ,.0060 ,.0070 ,50
18  .0065 ,.0060 ,.0065 ,.0075 ,.0060 ,.0075 ,52
19  .0035 ,.0035 ,.0035 ,.0045 ,.0035 ,.0035 ,50
20  .0040 ,.0040 ,.0050 ,.0068 ,.0050 ,.0045 ,52
21  .0058 ,.0035 ,.0030 ,.0025 ,.0030 ,.0035 ,7[illegible]
22  .0060 ,.0035 ,.0045 ,.0042 ,.0043 ,.0035 ,65
23  .0040 ,.0030 ,.0040 ,.0045 ,.0030 ,.0040 ,7[illegible]
24  .0055 ,.0085 ,.0065 ,.0095 ,.0065 ,.0080 ,65

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*REMOVE CLEARFILES
*LIST T-03-6

01 12,6
02 .0055/.0090,.0095,.0100, 1E11, 1E11, 44
03 .0095,.0105,.0125,.0105, 1E11, 1E11, 51
04 .0065,.0080,.0100,.0085, 1E11, 1E11, 63
05 .0085/.0100,.0120,.0125, 1E11, 1E11, 27
06 .0110,.0125,.0155,.0125, 1E11, 1E11, 3
07  1E11, 1E11, 1E11, 1E11, 1E11, 1E11, 62
08 .0075,.0140,.0130,.0115, 1E11, 1E11, 15
09  1E11, 1E11, 1E11, 1E11, 1E11, 1E11, 46
10 .0055,.0105,.0140,.0100, 1E11, 1E11, 15
11 .0090, 1E11,.0145,.0120, 1E11, 1E11, 39
12 .0095,.0105,.0130,.0110, 1E11, 1E11, 6
13  1E11, 1E11, 1E11, 1E11, 1E11, 1E11, 6

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APPENDIX E

GHILIT #3

SOURCE	SS	DF	M-SQUARE
A	1.128039E 05	1	1.128039E 05
B	1.520500E 04	2	7.602500E 03
C	3.460450E 03	1	3.460450E 03
D	1.670020E 01	1	1.670020E 01
AB	5.972986E 04	2	2.986493E 04
AC	1.612057E 05	1	1.612057E 05
AD	9.823406E 04	1	9.823406E 04
BC	1.322272E 03	2	6.611362E 02
BD	1.010608E 04	2	5.053039E 03
CD	5.201515E 04	1	5.201515E 04
ABC	2.242286E 05	2	1.121143E 05
ABD	5.884093E 03	2	2.942046E 03
ACD	3.084895E 04	1	3.084895E 04
BCD	1.336754E 04	2	6.683771E 03
ABCD	1.842755E 04	2	9.213776E 03
SSE	3.354002E 05	66.9	5.009908E 03
SST	1.142256E 06	89.9	1.269916E 04

APPENDIX F

LABORATORY CUTTER WEAR EVALUATION VERIFICATION TEST DATA

The following table describes the tests conducted in the production environment at Hooksett, NH.

TEST	DESCRIPTION	PURPOSE
1–20	Carboloy 883 in 2 spindles vs Ramet I in 2 spindles	To determine which material had better life (wear and chipping)
21–26	Ramet I in all 4 Spindles	To determine % increase in Cutter Life over baseline life (Time/ wear).
27	Ramet I in all 4 spindles to produce a full compressor section.	To determine the actual reduction in cutters to produce the five compressor components.

APPENDIX F

Tests 1-20 Carboloy 883 vs Ramet 1

All 4 tools were changed according to previous experience, i.e., a certain number of pockets, or operator discretion as far as smoking, excessive force (force meter), noise, or visual inspection of the cutter.

Tests 21-26 Ramet All 4 Spindles

All 4 tools were changed on the basis of wear and visual inspection of tools (chipping, burning, etc). Tools were run to approximate wear of Carboloy 883 and if tools showed no signs of chipping, burning, etc. would be run through another pocket.

Test 27

Each individual tool was changed as it met the conditions of the previous test.

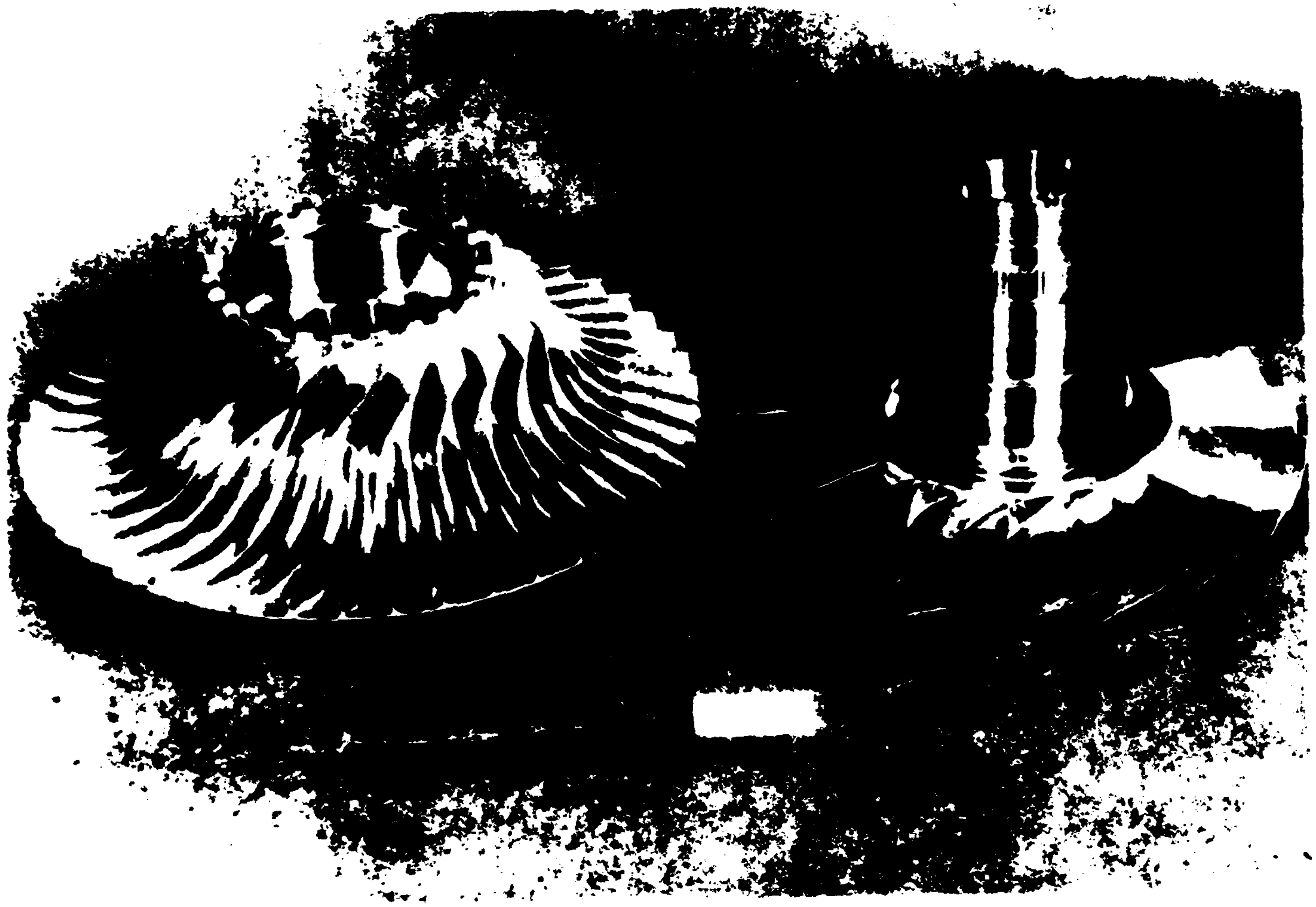
APPENDIX G

BLISK AND IMPELLER DESCRIPTIONS

The airfoils on blisks and impellers are machined on the disks or hubs which support them. Currently available airfoil volume production processes such as forging cannot be used to produce blisk and impeller airfoils because the existing processes are only suitable for making separate airfoils which are assembled to their disks after the airfoils are machined.

Blisk and impeller airfoils for development and early production T700-GE-700 engines were machined with manually controlled tracer milling, after which manual abrasive machining was used to generate final contours and surface texture. These processes are suited to low volume production but are not suitable for high volume production. Manufacturing costs with them are high because they are labor intensive. Also, airfoil quality is heavily dependent on manual skill. Furthermore, the time needed to introduce airfoil design improvements was too long.

There are five axial stages in the T700 engine compressor. The rotating components for these stages consist of four blisks. There is a Stage 1 blisk, a Stage 2 blisk, a Stage 3 and 4 blisk, and a Stage 5 blisk. There is also one centrifugal stage and the rotating component for this is an impeller. The centrifugal impeller and a Stage 1 blisk are shown in Figure G-1 (pg 98). The outside diameter of the Stage 1 blisk is approximately 7.7 inches and the outside diameter of the impeller is approximately 9.4 inches.



T700 CENTRIFUGAL IMPELLER

T700 STAGE 1 BLISK

Figure G-1. Impeller and Stage 1 Blisk.

APPENDIX H

FINAL SPECIFICATION FOR INSPECTION EQUIPMENT USED FOR END MILL CUTTER

D. Alexander Koso of A.K. Associates was chosen to develop a final specification for a single machine to inspect the complex geometry of end mill cutters. The specification is shown on the following pages.

APPENDIX H

FINAL SPECIFICATION FOR INSPECTION EQUIPMENT USED FOR END MILL CUTTER

1.0 SCOPE

This specification covers inspection equipment used to inspect end mill type cutters.

2.0 APPLICABLE DOCUMENTS

The following documents shall form a part of this specification. In cases where General Electric and other codesconflict, General Electric requirements shall apply.

2.1 General Electric Specification for the Electrification of Machine Tools and Industrial Equipment No. S1231-06, dated 10/30/72. When the purchase order references a Government Contract number, the requirements for exclusive use of General Electric components, is waived.

2.2 General Electric Specification for Electronic Industrial Equipment No. S1231-07, dated 6/3/73.

2.3 General Electric Specifications S1251-01, dated 5/22/75 (Electrical Grounding).

2.4 General Electric "Installation Data" Form No. DF-10, dated 3/24/69.

2.5 National Electric Code NFPA #70 (Latest Edition).

2.6 The latest revision of the Joint Industrial Council's Electrical Standards for General Purpose Machine Tools.

2.7 The latest revision of the Joint Industrial Council's Hydraulic Standards.

2.8 Applicable portions of the latest edition of the U.S. Department of Labor (Safety & Health Standards) Title 41, Part 50-204.

3.0 REQUIREMENTS

3.1 Background

Manufacturing experience has shown substantial variation between end mill type cutters. The purpose of the proposed equipment is to characterize the geometry of the cutting surfaces, to insure that the variation of performance of end mill type cutters is minimized when these cutters are used in multispindle production machines.

The equipment will also allow the operator to qualitatively examine the condition of the cutting edge and the finish of the grind.

APPENDIX H

FINAL SPECIFICATION FOR INSPECTION EQUIPMENT USED FOR END MILL CUTTER

Some general characteristics, e.g., number of flutes, diameter, flute length and runout can be measured with conventional mechanical gaging; they do not have to be measured by the special inspection equipment.

3.2 *Parameters to be measured by the inspection equipment.*

The parameters are grouped into five areas. (See Appendix H-1 for the definition of terms used in this specification.)

- General Characteristics
- End Geometry Characteristics
- End Cutting Edge Characteristics
- Side Cutting Edge Characteristics
- Corner (Blend Point) Characteristics
- The tolerance of each measurement is + or - the value specified

3.2.1 General Characteristics

3.2.1.1 Helix Angle

Required measurement accuracy is 2 degrees

3.2.2 End Geometry Characteristics

3.2.2.1 Diagonal Web Thickness

Required measurement accuracy is 0.005 inch

3.2.2.2 Walk Length

Required measurement accuracy is 0.005 inch

3.2.2.3 Gash Width

Required measurement accuracy is 0.005 inch

3.2.2.4 Gash Radius

Required measurement accuracy is 0.005 inch

3.2.2.5 Notch Radius

Required measurement accuracy is 0.005 inch

3.2.2.6 Dish Angle

Required measurement accuracy is 1 degree

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FINAL SPECIFICATION FOR INSPECTION EQUIPMENT USED FOR END MILL CUTTER

3.2.3 End Cutting Edge Characteristics

3.2.3.1 Width of Primary Land

Required measurement accuracy is 0.0005 inch

3.2.3.2 Primary Clearance Angle

Required measurement accuracy is .0001 inches in 0.005 inch

3.2.3.3 Axial Rake Angle

Required measurement accuracy is 1 degree

3.2.3.4 Axial Gash Angle

Required measurement accuracy is 1 degree

3.2.4 Side Cutting Edge Characteristics

3.2.4.1 Width of Primary Land

Required measurement accuracy is 0.0005 inch

3.2.4.2 Primary Clearance Angle

Required measurement accuracy is 0.0001 inch in 0.005 inch

3.2.4.3 Radial Rake Angle

Required measurement accuracy is 1 degree

3.2.4.4 Radial Rake Check

Required measurement accuracy is 1% of the cutter diameter.

3.2.5 Corner (Blend Point) Characteristics

3.2.5.1 Corner Radius

Required measurement accuracy is 0.0001 inch

3.2.5.2 Primary Land Width at Blend Point

Required measurement accuracy is 0.0005 inch

3.2.5.3 Gash Blend

Required measurement accuracy is 1 degree

APPENDIX H

FINAL SPECIFICATION FOR INSPECTION EQUIPMENT USED FOR END MILL CUTTER

3.2.6 Qualitative Inspection

3.2.6.1 The equipment should allow the operator to detect chips or voids larger than 0.0001 inch

3.2.6.2 The operator shall be able to examine the finish of the primary land under 50X magnification.

3.2.6.4 Gash Blend

The operator shall be able to observe any mismatch in the grind of the corner radius and determine the angle where the mismatch occurs.

3.2.6.5 Cutting Edge Inspection

The operator shall be able to examine the full length of a cutting edge in a continuous manner.

3.3 Operator Presentation

3.3.1 Parallax

The viewing system shall have minimal parallax between measurement reticles and the cutter image. The images shall be viewed through a long eye relief (3 inches) eye piece, or as a projection on a ground glass surface.

3.3.2 Field of View and Resolution

The operator shall be able to see the full diameter of a .5 inch diameter cutter and be able to resolve 0.0001 inch surface irregularities while viewing the full cutter diameter.

3.3.3 Zoom

The operator shall be able to zoom in on an area of interest when this area is at the center of the displayed field. The zoom capability shall be continuous and cover a magnification range of 20X to 50X.

3.4 Illumination

Both surface and background illumination shall be provided as required for the above measurements.

3.5 All positioning and rotation devices shall have digital readouts as required by the measurement accuracy. A BCD output from each translation and rotation axis shall be available for direct interfacing with a data acquisition system.

APPENDIX H

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3.6 Operating Speed

Once the equipment is set up for a specific cutter, the measurements shall be performed by a trained operator in less than TBD.

3.7 Representative Inspection System Configuration

A suggested measurement system configuration is shown in Appendix H-2. However, any configuration which can be used to make all of the required measurements is acceptable.

3.8 Operating Conditions

The equipment will be used in precision machining manufacturing facility. Temperature range 60-80 degrees Fahrenheit. Relative humidity 80%. No special facilities are contemplated for the installation of this equipment.

4.0 DOCUMENTATION

4.1 Operating and Installation Documents

4.1.1 As soon as the design and engineering of the equipment is completed, the vendor shall provide the customer design layouts including wiring diagrams for customer review and approval.

4.1.2 At time of shipment, the vendor shall provide one (1) complete set of reproducible electrical diagrams to JIC standards.

4.1.3 At least (2) weeks before delivery of the equipment, the vendor shall provide:

4.1.3.1 Three (3) copies of the maintenance manual and parts list and the recommended spare parts list, including preventative maintenance and lubrication instructions.

4.1.3.2 Three (3) separate copies of the operating instructions.

4.2 Program Plan

Within 30 days from receipt of the order, the vendor shall provide the General Electric Company with a plan showing times and sequences of major events during the construction and testing of the equipment.

4.3 Progress Reports

Monthly progress reports shall be supplied to the General Electric Company until completion of the order. However, the vendor shall notify the General Electric Company immediately of any projected changed in the schedule supplied under Item 4.2.

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5.0 TRAINING AND MAINTENANCE

The vendor shall provide operating and instruction manuals which will contain the following information:

5.1 Manuals

5.1.1 Detailed operating instructions including methods of set up and adjustment of all controls, safety devices and interlocks. Any special precautions that are required shall be specifically described in the manual. The vendor is responsible to supply similar information on purchased equipment being limited to the information available from these sources.

5.1.2 Detailed maintenance and service instruction, including a schedule of all service operations which should be performed regularly. Catalogs and maintenance manuals of equipment not manufactured by the vendor shall be included in the manual.

5.1.3 Detailed operating instructions on use and application of all control functions. Realistic typical examples are to be included for each application.

5.2 Spare Parts

The vendor shall provide a complete list of all spare parts which should be carried in stock by the customer.

5.2.1 The parts list shall list each part name and manufacturer together with part number, catalog number and other positive identification.

5.2.2 The recommended spare parts list shall be provided for buyer's approval in sufficient time to allow delivery of a complete set of spares to coincide with measuring machine delivery.

5.3 Approvals

Thirty days before the scheduled measuring machine delivery, the vendor shall submit for the customer's approval one draft copy of the operating and maintenance manual.

5.3.1 The customer shall respond with comments or approval of design drawings and manuals within two weeks after receipt of the document at the customer's plant.

APPENDIX H

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5.4 Training

The vendor shall include as part of the overall proposal and not a separate feature:

- All training deemed necessary at his plant
- All training required after installation at G.E.

Of particular importance is the thoroughness and quality of training. Tangible evidence of clear and concise instruction documentation will be required in advance of order placement.

6.0 WARRANTY

Assuming the equipment is used under normal operating conditions, all repair service and required replacement parts shall be provided free of charge to the General Electric Company by the vendor for a period of twelve (12) months from the date of final acceptance.

7.0 EQUIPMENT ACCEPTANCE

7.1 Vendor will submit for customer's approval a test program to demonstrate that the system will meet the requirements of the specification. This test will be demonstrated to customer's representative in his plant and again when installed in customer's plant.

7.2 Authorization to ship will be based on the successful completion of the equipment demonstrations at the vendor's plant.

7.3 Final acceptance will be made in the customer's plant and will be based on a successful demonstration that the equipment fully meets the requirements of this specification.

7.4 The vendor shall provide a service engineer in the customer's plant at no additional charge, for a time sufficient to install, start up the equipment, carry out the final acceptance per paragraph 7.3 and train operating personnel.

8.0 SHIPPING REQUIREMENTS

Upon acceptance for shipment, the vendor shall ship the equipment FOD vendor's dock to: General Electric Company, Aircraft Engine Group, Lynn, MA.

APPENDIX H-1

Nomenclature Used to Specify Cutter Characteristics
(See Figure H-1)

Paragraph	Drawing Notation	Nomenclature
3.2.1.1	B	Helix Angle
3.2.1.2	FA	Spacing Between Flutes
3.2.2.1	H	Diagonal Web Thickness
3.2.2.2	WL	Walk Length
3.2.2.3	W	Gash Width
3.2.2.4	U	Gash Radius
3.2.2.5	RN	Notch Radius
3.2.2.6	J	Dish Angle
3.2.3.1	K	Width of Primary Land
3.2.3.2	L	Primary Clearance Angle
3.2.3.3	G	Axial Rake Angle
3.2.3.4	T	Axial Gash Angle
3.2.4.1	F	Width of Primary Land
3.2.4.2	Q	Primary Clearance Angle
3.2.4.3	D	Radial Rake Angle
3.2.4.4	E	Radial Rake Check
3.2.5.1	C	Corner Radius
3.2.5.2	BL	Blend Point Primary Land Width
3.2.5.3	X	Gash Blend

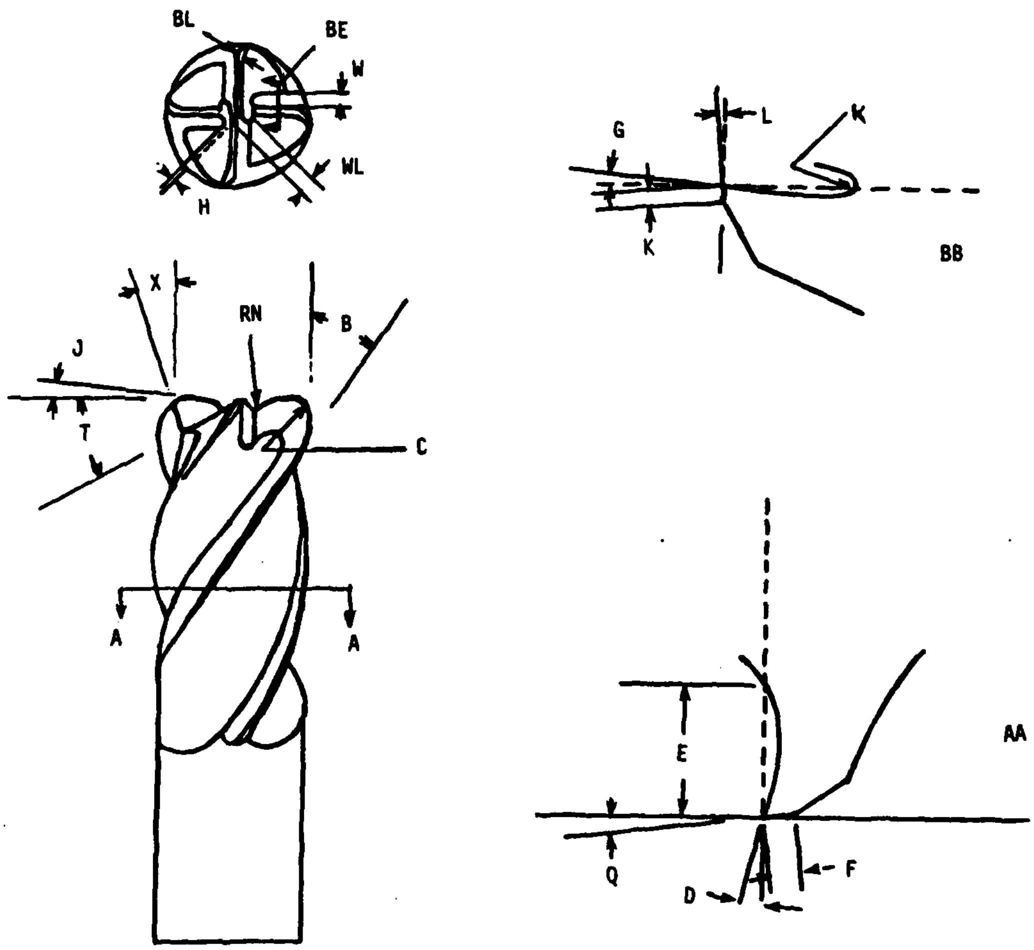


Figure H-1. Cutter Characteristics Nomenclature.

APPENDIX H-2

The following equipment can be assembled in a test station to perform the measurements specified in Section 3.

Special attention has to paid to paragraphs 3.2.3.3 and 3.2.4.3. The measurements specified can be performed near the blend point. The tool has to be rotated to a position such that, at the measurement point, a tangent to the cutting edge is essentially parallel to the optical axis of the instrument.

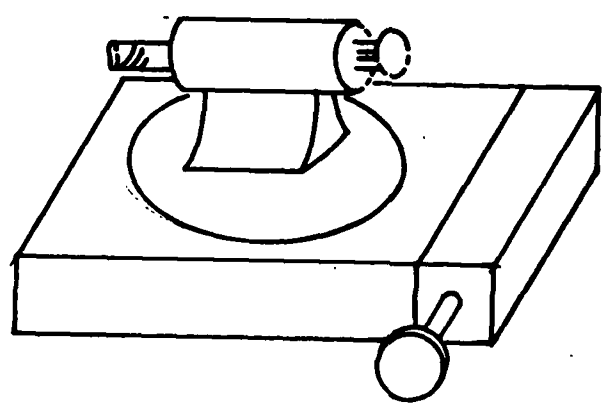
The other specified measurements can be performed using a combination of front and back lightning of the cutter.

The basic instrument used for the measurement can be a long eye relief microscope with a zoom objective and custom designed reticle. Rotation of the reticle is required for some measurement (e.g., Helix Angle). One quadrant of the reticle should contain concentric circles to enable the operator to measure the blend point radius. It is suggested that the microscope be configured to provide a horizontal line of sight between the tool and the microscope objective.

The zoom mechanism should have a detent position for the required quantitative measurements.

To allow examination of all of the cutting edges, the cutter can be mounted in a rotary fixture with its rotation axis along the tool rotation axis.

Since it is necessary to view the cutter from the side and also end on (and some points in between), the cutter holding fixture can be mounted on a rotary table as shown in the figure.



This assembly can be mounted on an x, y, z stage to provide motion of the cutter normal to the line of sight of the microscope and also to provide for focusing of the image on the microscope reticle. (It may be more convenient to allocate the x, y, z motion partially to the tool fixture and partially to the microscope assembly.)

APPENDIX H-2

Separate lights should be provided for the various measurements. The turning on and off of lights for the different measurements is acceptable, movement of the light source to provide the required illumination angle is not.

The components, including readouts for the translation and rotation stages, should be mounted on a small rigid surface. Storage for the tool holding fixture adapters (to accommodate various cutter diameters) and for the operation/maintenance manuals should be provided in the test station.

APPENDIX I

IAG CUTTER DRAWINGS

The drawings of the cutters were developed by the Interactive Graphics Department of Building 40 at Lynn, MA. These drawings were computerized for flexibility, give an excellent detail of cutter geometry, and are compatible with cutter grinding parameters (Figure I-1).

Computerized IAG's were also used to produce 3-dimensional images of an impeller roughing cutter (Figure I-2, pg 112) to determine the feasibility of using this graphics system as a cutter design aid. It was determined that the only way this system could be used effectively as a cutter design aid would be by post-processing the Huffman tape information and using it to control the graphics system. This could not be achieved within the scope of this program.

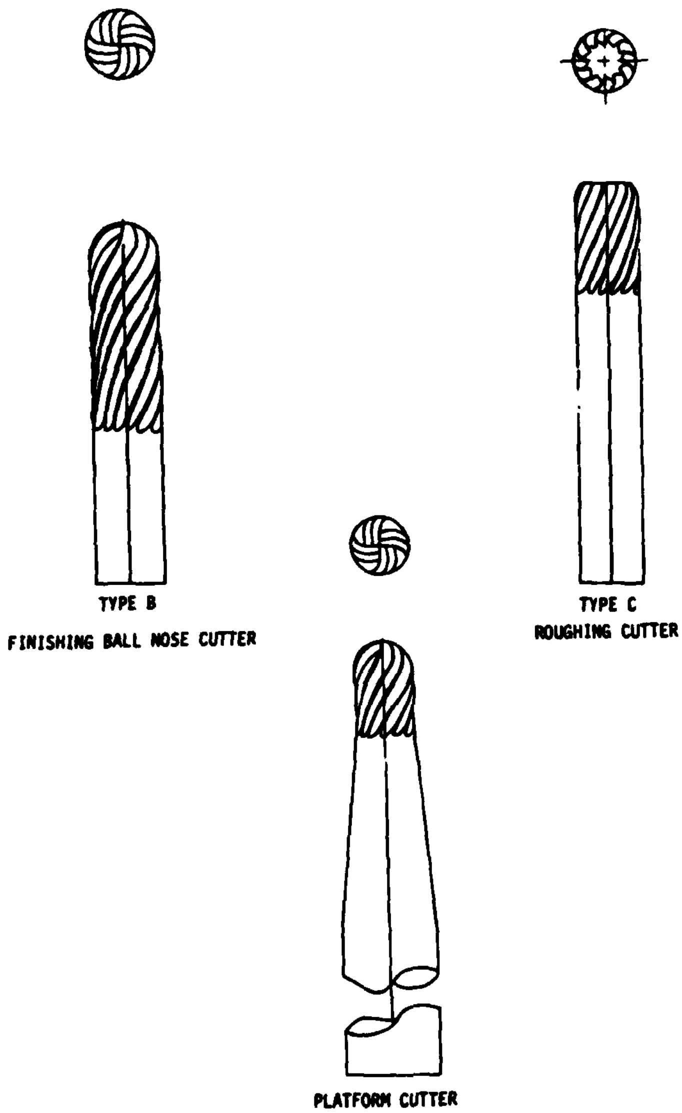


Figure I-1. Types of Cutters.

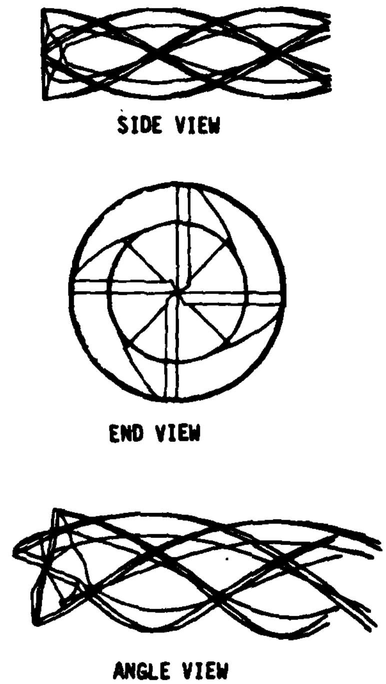


Figure I-2. 3-Dimensional Interactive Graphics Representation of a Cutter.

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